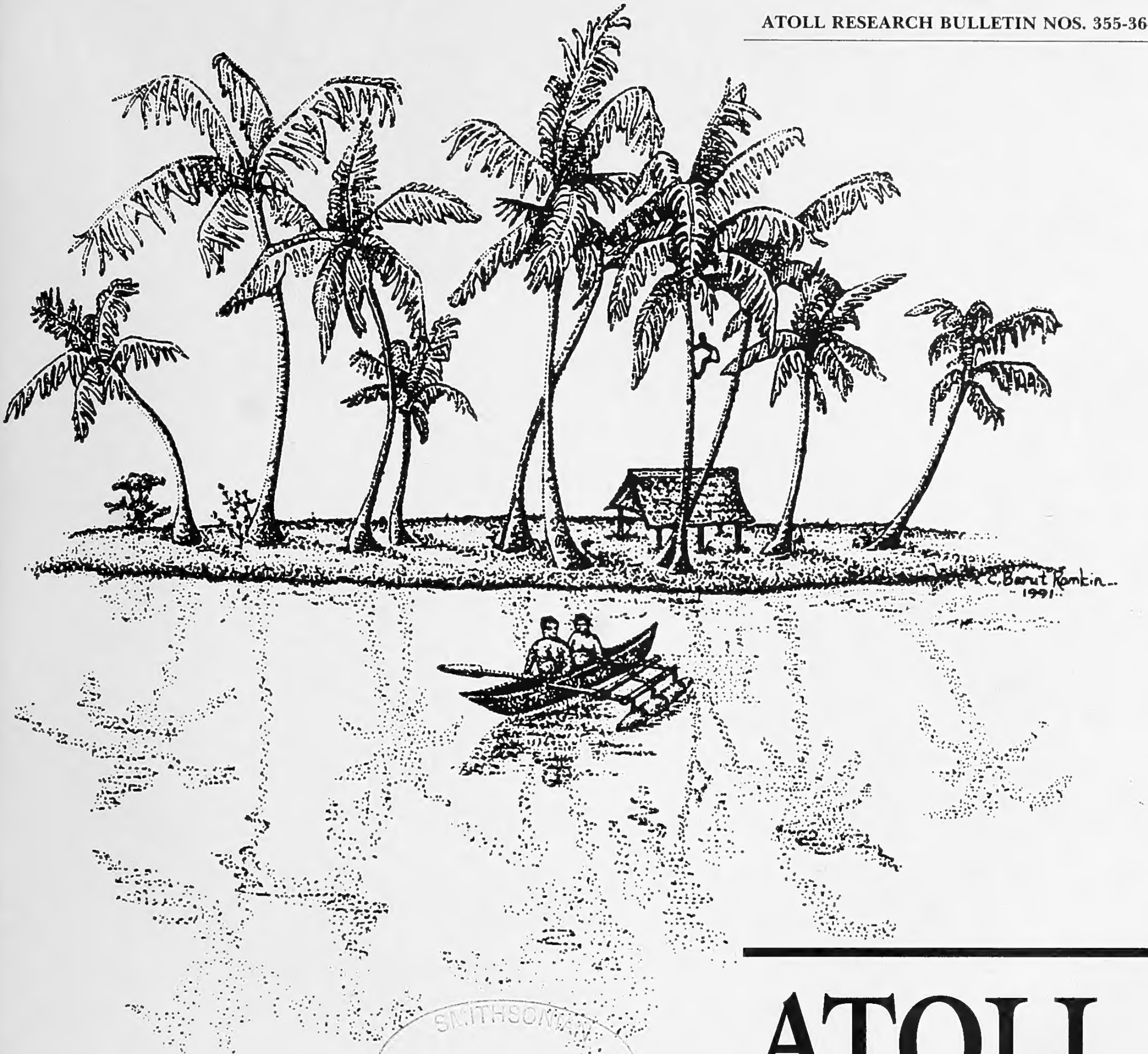


ATOLL RESEARCH BULLETIN

40TH ANNIVERSARY ISSUE

Issued by

NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C. U.S.A.
MAY 1992

40TH ANNIVERSARY ISSUE

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

ACKNOWLEDGMENT

The Atoll Research Bulletin is issued by the Smithsonian Institution, to provide an outlet for information on the biota of tropical islands and reefs, and on the environment that supports the biota. The Bulletin is supported by the National Museum of Natural History and is produced by the Smithsonian Press. This issue is partly financed and distributed with funds by readers and authors.

The Bulletin was founded in 1951 and the first 117 numbers were issued by the Pacific Science Board, National Academy of Sciences, with financial support from the Office of Naval Research. Its pages were devoted largely to reports resulting from the Pacific Science Board's Coral Atoll Program.

Articles submitted for publication in the Atoll Research Bulletin should be original papers in a format similar to that found in recent issues of the Bulletin. First drafts of manuscripts should be typewritten double spaced. After the manuscript has been reviewed and accepted, the author will be provided with a page format with which to prepare a single-spaced camera-ready copy of the manuscript.

ATOLL RESEARCH BULLETIN

NO. 355

F. RAYMOND FOSBERG AND THE ATOLL RESEARCH BULLETIN 1951-1991

BY

EDITED BY DAVID R. STODDART

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

Contents

F. Raymond Fosberg
June 1986

F. RAYMOND FOSBERG AND THE *ATOLL RESEARCH BULLETIN*, 1951-1991

BY DAVID R. STODDART[1]

The first issue of the *Atoll Research Bulletin* was dated September 10, 1951. To date, in 1991, 354 numbers of the *Bulletin* have been issued in 78 separate volumes, containing more than 600 separate titles. Then, as now, the *Bulletin* has been edited by F. Raymond Fosberg, joined over the years by a small team of associates of whom the most active and prominent was the late Marie-Hélène Sachet. In good times and in bad, Ray Fosberg has guided this journal to be the central repository of information concerning the biota and ecology of reefs and reef islands in all three tropical oceans. In addition to this editorial achievement—and let no-one underestimate the prodigious amount of work it has involved by the small staff in Washington, D.C.—Ray is a botanist and conservationist of worldwide reputation and extraordinary productivity. To mark the anniversary of the *Bulletin* his co-editors decided to honor him with this special issue of papers on themes close to his central interests. This issue is therefore dedicated to him.

The record of the *Bulletin* has been documented in extraordinary detail in the comprehensive index compiled by Mary McCutcheon and published appropriately in 1991. She records in her introduction how the *Bulletin* grew out of the Coral Atoll Program of the Pacific Science Board, headed by the late Harold Coolidge, and the remarkable series of expeditions sponsored by the Program to representative atolls across the Pacific. As she records, it was Ray who first proposed the concept of a formal bulletin to record the preliminary results of these expeditions, and who was also responsible for suggesting its title.

The critical initiatives which led to the foundation of the *Bulletin* came with the Pacific Science Board expedition to Arno Atoll in the southeastern Marshall islands in 1950 and early 1951, and the convening of symposia in Washington on 12 January 1951 and in Honolulu 5-6 February 1951 (Coolidge 1951). The first paper published in the first issue of the *Bulletin* was Ray's summary statement on 'Ecological research on coral atolls' (Fosberg 1951). While many other specialists contributed to these meetings, this statement effectively determined the philosophy adopted by the *Bulletin*. Since the first issue is now extremely difficult to find, this paper is reprinted here.

The preliminary symposium papers in the first two issues were followed in 1953 by the *Handbook for Atoll Research*, termed the second preliminary edition (Fosberg and Sachet, eds. 1953). Thirty-two papers gave succinct yet detailed guidelines for work in geography, meteorology, geology, hydrology, soil science, botany, zoology, marine ecology, anthropology and expeditionary work. Although nearly forty years old, these papers, dating from a time when field science was simpler than it is today, can still be read with profit—not least the concluding papers ('Hints on how to live on a boat' and 'Hints on living under restricted camp conditions').

The earliest substantive issues of the *Bulletin* (3-11 and 15-17) were devoted to the results of the Arno Atoll expedition, in papers which often not only recorded field data but systematised existing knowledge in specific subject areas and provided models of field procedures. There followed the results of the second expedition in 1951 to

[1]Department of Geography, University of California at Berkeley, Berkeley, California 94720, U.S.A.

Manuscript received 1 December 1991

Onotoa Atoll, southern Gilbert Islands, including a widely-quoted paper by Preston E. Cloud, Jr. (1952); the third expedition in 1952 to Raroia Atoll, in the Tuamotus, including early versions of classic papers by Norman D. Newell (1954a, 1954b) together with major papers in anthropology and cultural ecology; partial results of the fourth expedition in 1953 to Ifalik Atoll in the central Carolines; and substantial reports on the fifth expedition in 1954 to Kapingamarangi Atoll in the southeastern Carolines (Niering 1956, Wiens 1956) which were to play a substantial role in the development of MacArthur and Wilson's (1967) influential theory of island biogeography.

These results, which generated a completely new appreciation of the diversity of atoll geomorphology, biotas and ecology across a wide geographic range in the Pacific, coincided with the beginning of the flood of publications, appearing serially as Professional Paper 260 of the U.S. Geological Survey, based on intensive studies of atolls in the southern Marshalls (notably Bikini, Enewetak, Rongerik and Rongelap) during 1946-1952. The 'wonderfully detailed descriptions' (Revelle 1954, v) of the surface geology and morphology of these atolls given by Emery, Tracey and Ladd (1954) did for the physical understanding of the surface features of atolls what the largely ecological reports in the *Bulletin* did for the understanding of the ecology.

Ray Fosberg was himself in the northern Marshalls in 1951 and 1952, detailing the geology, hydrology, soils, vegetation and floristics of 21 atolls: his *Military Geography of the Northern Marshalls* appeared in 1956. The *Bulletin* itself carried many of the scientific reports from this expedition—on the plants (Fosberg 1955), sediments and soils (Fosberg and Carroll 1965) and birds (Fosberg 1966). Ray returned to Bikini in 1985 (Fosberg 1988), and rounded out his work in the Marshalls with a review of their natural history in 1990.

The 1950s thus saw an expansion of coral reef research on a quite unprecedented scale, in which the Pacific Science Board and the *Atoll Research Bulletin* played a central role. I myself saw my first atoll and barrier reef in 1959, and met Ray and Marie-Hélène Sachet the following year. With the generation of so much new research one was very conscious that coral reef studies were at the frontier of science, and at a time when the flood of new publications had not yet become the almost unmanageable torrent it has now become. At that time Ray and Marie-Hélène were working as botanists for the U.S. Geological Survey from the National Academy of Sciences annex near the State Department. In 1966 they moved to the Department of Botany, National Museum of Natural History, Smithsonian Institution. Up to that date the *Bulletin* had been issued by the Pacific Science Board, but from issue 118 in November 1967 it has been published by the National Museum of Natural History. Ray formally reached retirement age in 1978, and Marie-Hélène died in July 1986; she had been associated with Ray in Washington since 1949. Ray asked me to join him as an editor in 1969, and Ian G. Macintyre of the Department of Paleobiology, National Museum of Natural History, in 1979. Mark M. Littler and Joshua I. Tracey, Jr. of the Smithsonian and Bernard M. Salvat, then of the Ecole Pratique des Hautes Etudes in Paris, joined the editorial board in 1987.

Ray had of course been introduced to Pacific reefs and islands many years before the *Bulletin* began. From 1932 to 1937 he was a graduate assistant in the Department of Botany at the University of Hawaii, where he began a long association with Harold St John and where he took his Master's degree in 1935. It was from Hawaii that he embarked as assistant to St John on the now legendary Mangarevan Expedition to central and eastern Polynesia in 1934 (Gessler 1937, 1943). He thus became one of a group of men—Anderson, Buck, St John, Zimmerman, Emory, Kondo, Stimson, Cooke—who have dominated terrestrial scientific studies in Polynesia, largely from Bishop Museum, for half a century. The expedition took him to many remote islands, including Vostok,

Flint, Oeno, Rapa, and Maria. Ray's knowledge of Henderson in particular was of critical importance when proposals for its development arose in the 1970s (Fosberg et al. 1983). But after he left Hawaii his Pacific interests were necessarily interrupted by the long war years, when he was diverted to economic botany in Andean South America. In 1946, however, he was appointed Botanist to the Micronesian Economic Survey, and began a long series of visits to the Marianas, Carolines, Marshalls and Ryukyus. Many of the early papers on the Marianas and Ryukyus were published by the Office of the Engineer, U.S. Army, Pacific, but more recently there have appeared massive checklists of Micronesian dicots, pteridophytes, gymnosperms and monocots (Fosberg et al. 1979, 1982, 1987), together with contributions to an ongoing *Flora of Micronesia* in *Smithsonian Contributions to Botany* (1975-).

Ray also has a wide knowledge of the vegetation of Caribbean coral islands, with visits to Alacran in 1961, the Pedro Cays in 1962, the U.S. Virgin Islands from 1970 onwards, the Belize reefs in 1971 and 1972, the Dry Tortugas in 1981. His Indian Ocean work included visits to the Maldives in 1956 and to the Seychelles and Aldabra in 1968 and 1971, and many times to Sri Lanka. All have resulted in substantial publications notably the *Flora of Aldabra and neighbouring islands* (Fosberg and Renvoize 1980). He published an extensive checklist of the plants of the northern Great Barrier Reef in 1991. He also found the opportunity to organise and co-edit with M.D. Dassanayake *A Revised Handbook to the Flora of Ceylon* beginning in 1980 and now entering its eighth volume.

Not least of his contributions to island studies was the compilation with Marie-Hélène Sachet of *Island Bibliographies* (nearly 600 pages in 1955) and its *Supplement* (over 400 pages in 1971). He also organized and edited a remarkable symposium on *Man's Place in the Island Ecosystem* (1963) at the Pacific Science Congress in 1961. His exhaustive study of the Pacific collections made by J.R. Forster on Cook's second voyage is close to publication. His book with Dieter Mueller-Dombois and Ross McQueen on the vegetation of Pacific islands is virtually complete.

This astonishing record says nothing of Ray's tireless work for conservation around the world, nor of his interests in the humid tropics, the vegetation of the Americas, mangroves or biogeography. Altogether the list of his published works contains over 600 items, and of these about ten percent have appeared in the *Atoll Research Bulletin*. And it is of course for Ray's great contribution to the *Bulletin* and thus to the establishment of coral reef science that we present this special issue. We hope that the papers here will all speak to Ray's special interests in coral islands and the tropical Pacific. Those on Washington and Suwarrow present data on vegetation history and distribution, respectively. That on the Marquesas recalls Ray's interest in the high islands of eastern Polynesia. The paper on the soils and plants of the northern Marshall Islands addresses the main concerns of his expeditions in that area, especially in 1951 and 1952 and on which he himself has published extensively. The paper on phosphate rocks of Tuvalu takes up the arguments advanced by Ray in two important papers in 1954 and 1957. The paper on Nukutipipi gives new information on a hitherto almost unknown atoll in the Tuamotus. The papers on ethnobotany and cultural ecology highlight an area of science which Ray has always insisted to be important. Sadly these papers cannot adequately represent the range of his interests—the collection includes nothing on taxonomic botany, for example, nor on conservation. Nor can it begin to represent the vast range of his colleagues and co-workers around the world, some of whom joined in a symposium in his honor at the INTECOL meeting in Yokohama in 1990, the proceedings of which will shortly appear in *Pacific Science*.

It has been a privilege for everyone associated with the *Bulletin* to have been able to work with Ray Fosberg over the years to make it a success. His co-editors are proud to be part of his team. And the *Bulletin* will undoubtedly carry many more papers from his pen.

Acknowledgments

Ian Macintyre helped greatly in assembling this issue, as indeed, over the years, did Marie-Hélène Sachet. We are all greatly in the debt of Mary McCutcheon for compiling the comprehensive *Contents Lists and Indexes* for the *Bulletin*.

References

Cloud, P.E., Jr. 1952. Preliminary report on geology and marine environments of Onotoa Atoll, Gilbert Islands. *Atoll Research Bulletin*, 12, 1-73.

Coolidge, H.J. 1951. Introduction. *Atoll Research Bulletin*, 1, 2.

Dassanayake, M.D. and Fosberg, F.R., eds. 1980-. *A Revised Handbook to the Flora of Ceylon*. New Delhi: Amerind Publishing Co. Vol. 1 [and subsequent volumes].

Emery, K.O., Tracey, J.I., Jr. and Ladd, H.S. 1954. Geology of Bikini and nearby atolls. *U.S. Geological Survey Professional Paper* 260-A, i-xv, 1-265.

Fosberg, F.R. 1951. Ecological research on coral atolls. *Atoll Research Bulletin*, 1, 6-8.

Fosberg, F.R. 1954. Soils of the northern Marshall atolls, with special reference to the Jemo Series. *Soil Science*, 78, 99-107.

Fosberg, F.R. 1955. Northern Marshall Islands Expedition, 1951-1952. Land biota: vascular plants. *Atoll Research Bulletin*, 39, 1-22.

Fosberg, F.R. 1956. *Military Geography of the northern Marshall Islands*. Tokyo: Intelligence Division, Office of the Engineer, Headquarters U.S. Air Force (Far East). 320 pp.

Fosberg, F.R. 1957. Description and occurrence of atoll phosphate rock in Micronesia. *American Journal of Science*, 255, 584-592.

Fosberg, F.R., ed. 1963. *Man's place in the island ecosystem*. Honolulu: Bishop Museum Press. 264 pp.

Fosberg, F.R. 1956. Northern Marshall Islands land biota: birds. *Atoll Research Bulletin*, 114, 1-35.

Fosberg, F.R. 1988. The vegetation of Bikini Atoll 1985. *Atoll Research Bulletin*, 315, 1-28.

Fosberg, F.R. 1990. A review of the natural history of the Marshall Islands. *Atoll Research Bulletin*, 330, 1-100.

Fosberg, F.R. and Carroll, D. 1965. Terrestrial sediments and soils of the northern Marshall Islands. *Atoll Research Bulletin*, 113, 1-156.

Fosberg, F.R. and Renvoize, S.A. 1980. *The Flora of Aldabra and neighbouring islands. Kew Bulletin*, Additional Series, 7, 1-358.

Fosberg, F.R. and Sachet, M.-H., eds. 1953. Handbook for Atoll Research (second preliminary edition). *Atoll Research Bulletin*, 17, 1-129.

Fosberg, F.R., Sachet, M.-H. and Oliver, R.L. 1979. A geographical checklist of the Micronesian Dicotyledonae. *Micronesica*, 15, 41-295.

Fosberg, F.R., Sachet, M.-H. and Oliver, R.L. 1982. Geographical checklist of Micronesian Pteridophyta and Gymnospermae. *Micronesia*, 18, 23-82.

Fosberg, F.R., Sachet, M.-H. and Oliver, R.L. 1987. A geographical checklist of the Micronesian Monocotyledonae. *Micronesica*, 20, 19-129.

Fosberg, F.R., Sachet, M.-H. and Stoddart, D.R. 1983. Henderson Island (southeastern Polynesia): summary of current knowledge. *Atoll Research Bulletin*, 272, 1-47.

Fosberg, F.R. and Stoddart, D.R. 1991. Plants of the reef islands of the northern Great Barrier Reef. *Atoll Research Bulletin*, 348, 1-82.

Gessler, C. 1937. *Road my body goes*. New York: John Day, Reynal and Hitchcock. xx, 362 pp.

Gessler, C. 1943. *The leaning wind: the story of a voyage in the South Pacific*. New York: D. Appleton Century. xii, 267 pp.

MacArthur, R. and Wilson, E.O. 1967. *The theory of island biogeography*. Princeton: Princeton University Press. 203 pp.

McCutcheon, M. 1991. Contents list and indexes for the *Atoll Research Bulletin. Atoll Research Bulletin*, 347, 1-145.

Newell, N.D. 1954a. Expedition to Raroia, Tuamotus. *Atoll Research Bulletin*, 31, 1-22.

Newell, N.D. 1954b. Reefs and sedimentary processes of Raroia. *Atoll Research Bulletin*, 36, 1-35.

Niering, W.A. 1956. Bioecology of Kapingamarangi Atoll, Caroline Islands: terrestrial aspects. *Atoll Research Bulletin*, 49, 1-32.

Revelle, R. 1954. Foreword. *U.S. Geological Survey Professional Papers*, 260-A, iii-vii.

Sachet, M.-H and Fosberg, F.R. 1956. *Island Bibliographies: Micronesian botany, Land environment and ecology of coral atolls, Vegetation of tropical Pacific islands*. Washington, D.C.: National Academy of Sciences–National Research Council Publication 335, 577 pp.

Sachet, M.-H. and Fosberg, F.R. 1971. *Island Bibliographies Supplement: Micronesian botany, Land environment and ecology of coral atolls, Vegetation of tropical Pacific islands*. Washington, D.C.: National Academy of Sciences. 427 pp.

Wiens, H.J. 1956. The geography of Kapingamarangi Atoll. *Atoll Research Bulletin*, 48, 1-86.

ECOLOGICAL RESEARCH ON CORAL ATOLLS[1]

F. RAYMOND FOSBERG[2]

Coral atolls, scattered over a large part of the tropical seas of the world, provide a natural laboratory for research in tropical ecology that is unique and that has scarcely been utilized. Although a certain amount of marine research has centered around atolls, their biota is so simple that it has not attracted much attention from students of land ecology. However, this very simplicity provides a situation almost ideal for studies of total environment and of human adaptations to and effects upon an environment.

Ecological research may take many forms. Essentially, ecology is a point of view from which almost any subject matter may be considered, that which emphasizes the interrelationships of living things and their environments. One of the most interesting types of such research is the study of a situation to determine what organisms inhabit it, what effects the various characteristics of the situation have upon them, what effects they have on the physical surroundings, and, finally, what effects they have upon each other. This applies not only to individuals of different kinds, but also to members of one population of the same kind. The most severe competition of all is that between members of the same population. Further it must not be overlooked that man is, of all the kinds of organisms in almost any situation, the one that exerts the strongest and most general influence.

Situations are usually selected for study because they are representative of a class of similar ones, so that the results of the research may be applied to the others of the class and may be compared with the results of similar studies of other representatives to arrive at generalities. As in many other fields, the ecologist studying situations is able to adopt either of two very different approaches, that of studying one or a few examples intensively, or that of studying many examples but much less thoroughly. Which of these approaches is best is a philosophical question that is not likely to be solved very soon. It seems unquestionable, however, that where both methods may be applied to one problem, the results will be more sound than those from either one or the other.

The complexities dealt with by ecology are probably greater than those facing any other science. Involved are, necessarily, a complete knowledge of the physical situation and the organisms in it, and their characteristics, requirements, and behavior. This is merely basic information. Then the innumerable processes taking place must be detected and understood. Finally, the effects of these processes on each other and on the various organisms must be determined, and an understanding of the resultant of all of these processes and effects arrived at, which should be an understanding of the situation itself. This ideal final product, this understanding of total environment, is the ultimate objective of ecological research.

Its value is so apparent that it scarcely needs to be pointed out. Such understanding furnishes the only real basis for complete control over a situation, the only basis for predicting the consequences of any use or any alteration of any factor in an

---

[1]This paper was first published in *Atoll Research Bulletin*, 1 (1951), 6-8.

[2]Department of Botany, National Museum of Natural History, Smithsonian Institution, Washington, D.C.

Atoll Research Bulletin 355 (1992), 9–11.

environment, and the only possible basis for any rational sustained program for permanent habitation of any area by man or his dependent organisms. In other words, it is the only completely sound foundation for conservation and management of any segment of the total resources of the world we live in.

Most ecology gives the impression of being mired down in such a mass of complexity as to be getting nowhere, or of dwelling on single items out of context of the web of which they are a part. This is a logical result of the enormous complexity of almost all situations, and is likely to be extremely discouraging to one who has vision enough to see the whole picture.

The logical way out seems to be to begin with some of the simpler classes of situations. An understanding of some of these may well provide the methods and basis for approaching more complex ones. And, indeed, such an approach seems to have given the best results so far. The ecology of the far north, of deserts, of ponds and lakes, of certain grasslands, and of moorlands has made the most substantial progress.

Coral atolls provide another class of such simple situations, and one of the few possible ones in the tropics.

One of the reasons why a study of total environment is one of the most refractory and difficult of all lines of investigation is that it does not lend itself readily to an experimental approach, as the very process of experimentation will certainly modify the environment being studied. Ordinary experimental technique consists of keeping certain variables constant and manipulating others, in order to ascertain their effects. The nearest thing to a possibility of such an approach in studies of total environment is in a type of natural situation where certain factors are reasonably constant while others differ in various examples.

Coral atolls present nearly an ideal set of such situations. They are flat, eliminating all of the variables commonly associated with altitudinal differences. They are tropical and oceanic, eliminating significant temperature differences. They are calcareous, eliminating most significant substratum differences. They are structurally simple, minimizing hydrologic complexities. Their flora and fauna are small, reducing biological influences and making the biotic communities relatively simple. Thus a fairly understandable basic ecological pattern is discernible. Over this are laid variations in precipitation, size of island, distance from geographic sources of fauna and flora, period of human occupancy, cultural character of human occupancy, etc.

Understanding of the effects of these variable factors and of the functional dependencies between them and other factors may be approached by making comparative studies of several different atolls exemplifying differences in such variables as mentioned above. Comprehensive studies, such as those made on Arno by a team of workers, would be highly significant if available in advance for, say, a small dry atoll in the central Pacific, a small moist atoll in the central Pacific, a moderate sized moist atoll remote from large land areas such as in the Tuamotus, an uninhabited moist atoll, possibly Maria in the Australs, and an atoll near large land areas, such as one in the Melanesian area, i.e. Sikaiana.

If, over a period of several years, such a series of detailed, integrated investigations might be made, a fairly broad base of modern reliable comparative information would be established. Into this would be integrated the enormous amount of existing information being brought together by the bibliographic phase of the investigation. As a result it might be possible that a coherent and understandable picture

of a limited tropical total environment would emerge, comparable to that developed for English mountains and moorlands by Pearsall (1949).

The significance of this in terms of human values is quite clear. There is no question that, in spite of the limitations of this atoll type of environment, human populations are going to live there, just as they have for many hundreds of years, at least. Atoll peoples had, left to themselves, evolved a mode of life very well fitted to this environment, and in a fair equilibrium with it. Though rigorous and simple, it was, so far as we may know, a happy and satisfactory existence. These people had come to terms with their environment and made the necessary adaptations for life in it.

During the past century and a half, expanding Western European Civilization has burst in upon these self-contained microcosms, inevitably shattering the equilibria established over the previous centuries. Disease, an altered religion, commerce, war, and confusion were the gifts of this alien culture. To some this change may be a matter of regret, to others merely a matter of intellectual interest, to still others it is moral elevation, while some call it "progress". At any evaluation it must be accepted as a fact, and as irreversible. Modern transportation has become so effective that isolation, even for these remote atolls, no longer exists. The influence of western culture must now be reckoned with as a factor in any new equilibrium that is brought into being. Life for these peoples is thereby enormously complicated.

If modern science is to be of any real benefit to these peoples, as well as to others, it is probable that it must be in helping them to come to terms again with their environment, the new environment that has resulted from the shattering of the old. It is here that ecology, particularly the aspect of it dealing with understanding of total environment, is of vast importance. Understanding is certainly the first requisite toward dealing with anything. If this study of atolls contributes, over the years, to the readaptation of atoll peoples to their place in the world, as well as providing a key to the understanding of other, more complex total environments, it will have amply justified itself.

PACIFIC OCEANIC ISLAND BIODIVERSITY IN A GEOHISTORIC PERSPECTIVE[1]

BY F. RAYMOND FOSBERG[2]

Cosmologists, geophysicists, geologists, paleontologists and evolutionists—speculators all beyond their own sciences—have given us a scenario of an earth starting as a featureless accumulation of matter, showing a continuing, possibly at times interrupted, increase of diversity. At first, apparently, contracting and consolidating into a lifeless globe, the earth eventually differentiated into a lithosphere, hydrosphere and atmosphere, intercepting energy from the sun. At some period in its first few billions of years, the right assemblage of carbon and nitrogen compounds, with hydrogen and oxygen, occurred, and what we know as life began. Catalytic influences stimulated the formation of amino-acids, protein chains, and, eventually, photosynthetic pigments that fixed energy from sunlight. Aggregations of these compounds occurred that became autocatalytic, self-reproducing, and the wondrous spectacle of life and organic evolution began.

Meanwhile, physical diversity of the earth's surface developed, providing different environments for the simple bits of akaryotic protoplasm to inhabit. Cell-walls and membranes somehow came into being, enclosing self-reproducing bits of autophytic protoplasm, now called cells. A next step, providing a mechanism for much greater evolution of diversity, was the appearance of karyotic cells with nucleus and chromosomes. As diversity further developed, different habitats harbored the living cells and colonies of cells, and the different habitats selected variants of these organisms with different adaptations to match the habitats. The reproductive potential of some of these variants began to exceed the available habitats. Competition and natural selection began. All of this during hundreds of millions or perhaps several billions of years. The earth cooled, dry land appeared, compounding the opportunity for diversity. Meanwhile, even before the appearance of karyotes, some of the kinds of cells acquired the character of forming hard calcareous or siliceous cell walls, and, dying, leaving their shells to become the earliest fossils.

With natural selection, more than chance diversification came into being. Evolution became a process, more and more multidirectional. More of its products left skeletons, and even chemical impressions, as fossils, and some of the speculations of future evolutionists became founded on the beginnings of factual bases. With mitosis, multicellular organisms, and sexual reproduction, evolutionary diversity or biodiversity proliferated in all directions and in all dimensions. Of course, all along, the majority of forms evolved were incapable of self-sustainment and disappeared. And the diversity of habitats could not possibly keep up with the geometrical increase of forms of organisms. So limits of habitat diversity came to limit organic or biological diversity. The ecosphere or thin layer of habitable space on the earth's surface became populated with millions of species and untold millions of competing individuals.

---

[1]This is the text of a plenary address at the XVII Pacific Science Congress, Honolulu, Hawaii, May 1991. It has been published in the *Proceedings* of the Congress, pp. 71-73, and is reprinted with permission.

[2]Department of Botany, National Museum of Natural History, Smithsonian Institution, Washington, D.C.

Atoll Research Bulletin 355 (1992), 13–17.

Geographical diversification had also been going on for geological aeons, some ages after Pangaea separated into continents, and the earth's crust into infinitely slowly moving tectonic plates. More familiar global geography began to appear. Eventually, after some ages of continental movement and rearrangement, the Pacific Ocean and Pacific basin slowly took shape, the Pacific Ocean came into being, and our Pacific scenario began. By this time there were myriads of organisms, a few of which left fossilized remains. These, when studied, helped fill in the details, but the big picture is reconstructed by what I call *physiographic fossils*.

These take such forms as wrinkles in the earth's crust, mountain chains, island arcs, chains of seamounts and guyots, subduction zones, earthquake foci, extinct volcanoes, coral atolls, elevated coral islands, mid oceanic ridges, and deposits of sediments on the sea floor. Interpreting these, our geophysicists can tell us now far more about the geohistory of the Pacific segments of the earth's crust and surface than anyone could have dreamed of when I first became interested in Pacific phenomena more years ago than I like to realize. If they want to, some of them can even tell us this in terms that an ordinary educated person can understand.

To come to the subject of this paper, we even know now something of how oceanic islands came into being. True oceanic islands are those that have never had any connection with continental land or major islands. They are all, with several controversial exceptions, volcanoes that arose from the ocean floor and reached the sea-surface. In the Pacific area these volcanoes can mostly be sorted into two classes—basaltic shield volcanoes, and andesitic cones. The shield volcanoes occur in the interiors of the Pacific and other tectonic plates. The cones are along the plate margins, where one plate is slipping under the edge of another, a process called subduction. Magma formation and diversification takes place in these contacts. Volcanoes and earthquakes are numerous in such zones.

The shield volcanoes apparently occur where a weak portion of a plate moves over a "hot spot", a place in the earth's mantle that serves as a conduit, where intense energy from the earth's interior comes through, where the heat is sufficient to melt the overlying rock into magma, a liquid rock. This pours out through vents or fissures in the sea-floor and, over the millions of years, builds up piles of solidified magma, or lava, which reach the sea-surface as island volcanoes. All of this geophysical activity is on an incredibly slow time-scale, but continually contributes to geographic diversity. This provides new habitats to accommodate and stimulate new biodiversity.

As the vast Pacific took shape, volcanoes on the sea floor may already have been forming. We have little or no information on what was happening there before perhaps 70,000,000 years ago. We can be reasonably sure though that a diversity of marine life occupied the Pacific Ocean from its beginning. We can speculate, also, that terrestrial plants and animals inhabited the surrounding land-masses, and that currents, storm winds and birds carried propagules into this watery space. How early there were islands there to be populated we can only guess. But volcanic islands did start to form, and evidence of them still exists in the form of seamounts and guyots, as well as coral atolls, the most ancient existing oceanic islands.

We can visualize a time, many millions of years ago, when there were new volcanic islands irregularly scattered in the Pacific, mostly bare lava-dome surfaces, with little environmental diversity, but beginning to erode and subside, terrestrial living organisms were probably there, but very thinly scattered indeed. The few different habitats that existed at first were suitable only for the most extreme pioneer forms. Spores of cryptogramic plants were, in all probability, the earliest propagules to arrive

and the likeliest to find conditions that permitted survival. Those of species with photosynthetic capacity would, of necessity, have been the first successful colonists, but likely would have been simple, probably unicellular plants, but capable of creating minute amounts of organic matter. More complex plants, hermaphroditic or monoecious, capable of reproducing themselves and utilizing the products of rock-weathering and the slight traces of organic matter would have "soon" followed, forming eventually a very simple vegetation and habitats for decomposers and pioneer animals which could consume or decompose raw organic matter. Simple, open ecosystems thus formed would have permitted more diverse colonists to survive. In these open habitats, with little or no competition, organisms with reasonable mutation rates might well have experienced relatively rapid evolution and, as habitats diversified, rapid diversification. Early island faunas and floras may have evolved relatively rapidly, in terms of thousands or millions of years. Every now and then, new and more advanced colonists might have arrived from the surrounding continental areas, to help colonise the increasingly numerous distinct habitats. These new arrivals might also have taken advantage of unoccupied niches, undergoing adaptive radiation and effecting more thorough utilization of available resources.

These early islands, of course, meanwhile underwent erosion and subsidence. Their faunas and floras would, as they developed, be sources for colonists for other islands, young or old. A Pacific terrestrial biota developed through such processes, and diversity increased, though islands eventually may have disappeared and new ones formed.

Because enormous water-barriers existed to slow down migration, this biota, and its sub-biotas, were never large. Nor was it as completely "harmonic" (with a full representation of the plant and animal families and orders) as those of continental regions, nor was change as rapid. Niches tended to remain broader, and some perhaps vacant.

The above, perhaps somewhat fanciful, history brought about the relatively recent major pattern, for which we now have much better evidence than imagined for the earlier stages.

We now had an ocean of its present size and configuration, with a large assortment of islands in all stages of formation, development and decline. Biotas resulting from original colonization from all surrounding regions were, after long isolation, largely endemic ancient relicts, presently flourishing, and newly evolving groups of plants and animals. There was not the great diversity found on continents, but a unique diversity, peculiar to island situation. The formative and declining processes were going on, slowly, as they had for ages. Some species were more dominant, some less, others rare and tenuously hanging on; most were endemic, found nowhere else.

The stage was set for Man, the dominant organism, to arrive on the scene.

Man, of diverse races, had been in the continental and continental island areas around the western Pacific for many thousands of years, in Australia, New Guinea, Malesia, southeast Asia, the Philippines and east Asia. Immigration of a number of very different racial stocks and much differentiation of local races had taken place. For a long time, apparently the wide water barriers between the continental areas and the oceanic islands were effective, and the oceanic islands lacked human inhabitants. But 4000 or more years ago several different cultural groups developed the arts of canoe-building and navigation to the point of making long voyages, and Micronesia and Polynesia were thoroughly explored and the habitable islands populated. Several different cultural complexes developed. The most widespread and one of the most culturally advanced

were the Polynesians who visited and settled islands as far-flung as Hawaii, the Marquesas, Easter Island and New Zealand. Some think, with good reason, that they have even reached South America.

This penetration of the erstwhile isolated and slowly changing oceanic islands brought profound changes. The new culture brought an abrupt increase in a new kind of diversity that associated with human activity. New plants and animals came with the human immigrants. Forests were cleared in the lowlands. Organisms requiring specialized habitats were displaced and disappeared. New plant communities involving exotics were assembled. New ecosystems, including human beings, were established, and as the newcomers multiplied, displaced certain indigenous ones. Birds, which were an important element in the pre-human ecosystems, became scarcer and many species disappeared, as man was also an effective predator. There may have been a net gain in diversity, but diversity was lost as well as gained. In any event, there were great changes, and many organisms, especially large and conspicuous ones, became extinct. Even now, their bones are being excavated and studied. The full extent of this loss may never be known. However, most of the uplands did not change much. For a long time mainly the coastal areas and valley bottoms were inhabited by humans. Of larger vertebrates, other than birds and marine animals, totally lacking up to now, only the dog, pig and chicken came with the people. The rat came too.

Island floras and faunas were conspicuously lacking in defensive mechanisms against herbivorous invaders. Spines, prickles, stinging hairs, acrid or poisonous sap, bad odors, were only found in clearly recent colonists which brought these features with them. Many island birds were flightless or ground nesting. Thus pigs and dogs could have a serious effect on the native biota. The extent of these effects are only recently becoming known, with paleontological studies, especially on deposits of fossil bird bones. The extent and environmental effects of ancient Hawaiian agriculture have recently been demonstrated by Patrick Kirch to have been much more widespread and to have had more influence than previously suspected.

Not much is known of the period between the spread of aboriginal people through Polynesia and Micronesia and the coming in the 15th to 18th centuries of European explorers. It seems certain that natural biodiversity declined some, but some degree of equilibrium may have been reached. All too little was recorded, by the first explorers, of environmental conditions at the time of European contact.

The arrival of Europeans brought vast and drastic changes to the Pacific islands. The cultural impact resulted in changes in life style, new implements, weapons, alcohol, religion, and a cash economy. A different attitude towards the environment resulted in over-exploitation, loss of indigenous natural diversity, substitution of a new diversity comprising European architecture, plantation agriculture, new economic plants and domestic animals, which went feral, and accompanying weeds and diseases. Ultimately came modes of transportation, machinery, and imported food and goods, worst of all a disdain for the old ways of life. Aboriginal populations declined and were replaced by immigrants.

In terms of effects on natural or biological diversity, probably the most serious complex of occurrences was the escape and naturalization of domestic herbivores and introduction and naturalization of exotic plants—edible ones, cultivated ornamentals, and weeds.

Most native vegetation types were closed forests, with the environmental or ecological niches mostly fully occupied. This vegetation was relatively stable, well

adjusted to its habitats. However, the history of complete lack of large herbivores had resulted in no natural defenses or protection against their trampling or browsing. Uninterfered with, the native forests were seldom invaded by exotics. Pigs had come with the aborigines and had initiated some disturbance. The introduction by the Europeans of cattle, goats, sheep, donkeys, horses, and, later, deer had a catastrophic effect. The forests were opened up, trampled, browsed, their structure broken down. This in itself initiated accelerated erosion. But the main effect was to permit the establishment of exotic plants, which, with continued effects of trampling and browsing, tended to out-compete and supplant the native species, and change the character of the vegetation. Goats, especially, over browsed both native and introduced plants, exposing the soil and deeply weathered rock to erosion, preventing revegetation. Floods occurred, streams became intermittent, coral reefs were silted and killed.

The fascinating indigenous floras, with numerous unique endemic species and even genera, were gradually replaced by the widely distributed pantropical flora.

Wherever there were fairly large, relatively flat and fertile lowland areas, their vegetation was completely replaced by coconut, sugar and pineapple plantations. Some areas, even small ones, were occupied by human habitations, industry, roads, towns and cities. Human occupation crept up the lower slopes, already altered to exotic rather than native vegetation.

Introduced bird diseases, rats, mongooses, and aggressive exotic birds eliminated lowland bird faunas and even some from the mountain slopes. Exotic birds were introduced and became established.

Even mountain peaks were utilized for beacons, relay stations and observatories, with roads built to them.

We have not mentioned military establishments and weapons, among the most wasteful and destructive of all human activities. These introduced some types of diversity, but wiped out many forms of indigenous biological diversity.

It is hard to estimate the net loss or gain of total diversity. The concept is hard even to define when applied to cultural effects. "Civilization" has, without doubt, brought about great decline and loss in biodiversity, most of it never to be regained.

Fortunately in very recent years there has grown a rather wide concern about loss of biodiversity, and efforts are being made to slow down or even prevent further loss, where practical. However, money concerns are much stronger than those about environmental matters. Almost always, money wins. Unless this attitude changes soon, most important islands, as well as general diversity, may disappear. A dreary world will be the result, at best. Granted the worst scenario, we may not even be here to experience it.

MAJOR PUBLICATIONS OF F. RAYMOND FOSBERG ON TROPICAL ISLANDS AND CORAL ATOLLS: A SELECTED LIST

[Note: this list does not include any of Dr. Fosberg's shorter taxonomic papers]

The genus *Gouldia*.
Bulletin of the Bernice P. Bishop Museum, 47 (1937), 1-82.

Some Rubiaceae of southeastern Polynesia.
Occasional Papers of the Bernice P. Bishop Museum, 13 (1937), 245-293.

Melanesian vascular plants.
Lloydia, 3 (1940), 109-124.

The Polynesian species of *Hedyotis*.
Bulletin of the Bernice P. Bishop Museum, 174 (1943), 1-102.

Micronesian mangroves.
Journal of the New York Botanic Garden, 48 (1947), 128-138.

Végétation et flora de l'atoll Maria, îles Australes.
Révue scientifique du Bourbonnais et du Centre de la France, 1951 (1952), 1-7.

Vegetation of central Pacific atolls: a brief summary.
Atoll Research Bulletin, 23 (1953), 1-26.

Soils of the northern Marshall atolls, with special reference to the Jemo Series.
Soil Science, 78 (1954), 99-107.

Northern Marshall Islands Expedition, 1951-1952. Narrative.
Atoll Research Bulletin, 38 (1955), 1-36.

Northern Marshall Islands Expedition, 1951-1952. Land biota: vascular plants.
Atoll Research Bulletin, 39 (1955), 1-32.

Island Bibliographies: Micronesian Botany, Land environment and ecology of coral atolls, Vegetation of tropical Pacific islands [with M.-H. Sachet].
National Academy of Sciences–National Research Council Publication 335 (1955), 577 pp.

The palms of Micronesia and the Bonin Islands [with H. E. Moore].
Gentes Herbarum, 8 (1956), 422-478.

Military Geography of the northern Marshall Islands.
Tokyo: Intelligence Division, Office of the Engineer, Headquarters U.S. Air Force (Far East) (1956), 320 pp.

Atoll Research Bulletin 355 (1992), 19–24.

Description and occurrence of atoll phosphate rock in Micronesia.
American Journal of Science, 255 (1957), 584-592.

Vegetation and flora of Wake Island.
Atoll Research Bulletin, 67 (1959), 1-20.

The vegetation of Micronesia.
Engineer Intelligence Study 257 (1959), 160 pp.

Vegetation [of Guam].
Military Geology of Guam, Mariana Islands, ed. J. I. Tracey, Jr. (Intelligence Division, Office of the Engineer, HQ U.S. Army Pacific) (1959), 167-217.

The vegetation of Micronesia. 1. General descriptions, the vegetation of the Marianas Islands, and a detailed consideration of the vegetation of Guam. *Bulletin of the American Museum of Natural History*, 119 (1960), 1-76.

Vegetation [of Ishigaki-Shima].
Military Geology of Ishigaki-Shima, Ryukyu-Retto, ed. H. E. Foster (Intelligence Division, Office of the Engineer, HQ U.S. Army Pacific) (1960), 51-84.

Vegetation [of the Miyako Archipelago].
Military Geology of the Miyaki Archipelago, Ryukyu-Retto, ed. D. B. Doan (Intelligence Division, Office of the Engineer, HQ U.S. Army Pacific) (1960), 165-187.

Qualitative description of the coral atoll ecosystem.
Atoll Research Bulletin, 81 (1961), 1-11.

Description of Heron Island.
Atoll Research Bulletin, 82 (1961), 1-4 .

Vascular plants of Heron Island [with R. F. Thorne].
Atoll Research Bulletin, 82 (1961), 5-13.

Soils, flora and vegetation [in: A report on typhoon effects upon Jaluit Atoll].
Atoll Research Bulletin, 75 (1961), 47-49, 51-55, 57-68, 95-104 .

Vascular plants recorded from Jaluit Atoll [with M.-H. Sachet].
Atoll Research Bulletin, 92 (1962), 1-39.

A brief study of the cays of Arrecife Alacran, a Mexican atoll.
Atoll Research Bulletin, 93 (1962), 1-25.

Man's place in the Island Ecosystem: a Symposium [organized and edited by F. R. Fosberg]. Honolulu: Bishop Museum Press (1963), 264 pp.

The Island Ecosystem.
Man's place in the Island Ecosystem: a Symposium, ed. F. R. Fosberg (Honolulu: Bishop Museum Press) (1963), 1-6.

Terrestrial sediments and soils of the northern Marshall Islands [with D. Carroll].
Atoll Research Bulletin, 113 (1965), 1-156.

Northern Marshall Islands land biota: birds.
Atoll Research Bulletin, 114 (1966), 1-35.

List of Addu vascular plants [with E. C. Groves and D. C. Sigee].
Atoll Research Bulletin, 116 (1966), 75-92.

The oceanic volcanic island ecosystem.
The Galapagos, ed. R. I. Bowman (Berkeley: University of California Press), 55-61.

Vascular plants.
Atlas for bioecology studies in Hawaii Volcanoes National Park, ed. M. S. Doty and D. Mueller-Dombois (Hawaii Botanical Society Papers, 2) (1966), 153-238.

Observations on vegetation patterns and dynamics on Hawaiian and Galapageian volcanoes.
Micronesica, 3 (1967), 129-134.

Wake Island vegetation and flora [with M.-H. Sachet].
Atoll Research Bulletin, 123 (1969), 1-15.

Plants of Satawal Island, Caroline Islands.
Atoll Research Bulletin, 132 (1969), 1-13.

A collection of plants from Fais, Caroline Islands [with M. Evans].
Atoll Research Bulletin, 133 (1969), 1-15.

Preliminary survey of Aldabra vegetation. *Philosophical Transactions of the Royal Society of London*, B 260 (1971), 215-225.

Geomorphology of Aldabra Atoll [with D.R. Stoddart, J.D. Taylor and G.E. Farrow].
Philosophical Transactions of the Royal Society of London, B 260 (1971), 31-65.

List of Diego Garcia vascular plants [with A.A. Bullock].
Atoll Research Bulletin, 149 (1971), 143-160.

The fern vegetation of Aldabra Atoll.
American Fern Journal, 61 (1971), 97-101.

Island Bibliographies Supplement: Micronesian Botany, Land environment and ecology of coral atolls, Vegetation of tropical Pacific islands [with M.-H. Sachet].
Washington, D.C. National Academy of Sciences (1971), 427 pp.

Geomorphic cycle on Aldabra—hypothesis.
Proceedings of the Symposium on Corals and Coral Reefs (Marine Biological Association of India, Mandapam Camp, 1969) (1972), 469-475.

List of vascular plants [of Rarotonga reef islands].
Atoll Research Bulletin, 160 (1972), 9-13.

South Indian sand cays [with D.R. Stoddart].
Atoll Research Bulletin, 161 (1972), 1-23.

Partial flora of the Society Islands: Ericaceae to Apocynaceae [with M.L. Grant and M.-H. Sachet].
Smithsonian Contributions to Botany, 17 (1974), 1-69.

Flora of Micronesia. 1. Gymnosperms [with M.-H. Sachet].
Smithsonian Contributions to Botany, 20 (1975), 1-15.

Phytogeography of atolls and other coral islands.
Proceedings of the Second International Symposium on Coral Reefs, 1 (1975), 389-396.

Flora of Micronesia. 2. Casuarinaceae, Piperaceae, and Myricaceae [with M.-H. Sachet].
Smithsonian Contributions to Botany, 24 (1975), 1-28.

Identification of vascular plants of Namoluk Atoll, Eastern Caroline Islands.
Atoll Research Bulletin, 189 (1975), 23-48 .

Coral island vegetation.
Biology and Geology of Coral Reefs, ed. O. A. Jones and R. Endean (New York: Academic Press) (1976), 3, 255-277.

Phytogeography of Micronesian mangroves.
Proceedings of the International Symposium on Biological Management of Mangroves (Gainesville, 1975), 1, 23-42.

Flora of the northern Marianas [with M. V. C. Falanruw and M.-H. Sachet].
Smithsonian Contributions to Botany, 22 (1975), 1-45.

Flora of Micronesia. 3. Convolvulaceae.
Smithsonian Contributions to Botany, 36 (1977), 1-34.

List of vascular plants [of Aitutaki reef islands, Cook Islands].
Atoll Research Bulletin, 190 (1975), 73-84.

Distribution of seagrasses in Micronesia [with R. T. Tsuda and M.-H. Sachet].
Micronesica, 13 (1977), 191-198.

A geographical checklist of the Micronesian Dicotyledonae [with M.-H. Sachet and R. L. Oliver].
Micronesica, 15 (1979), 41-295.

The Flora of Aldabra and neighbouring islands [with S. A. Renvoize].
Kew Bulletin, Additional Series, 7 (1980), 1-358.

Flora of Micronesia. 4. Caprifoliaceae-Compositae.
Smithsonian Contributions to Botany, 46 (1980), 1-71.

A Revised Handbook to the Flora of Ceylon [edited by M. D. Dassanayake and F. R. Fosberg].
New Delhi: Amerind Publishing Co. Volume 1 (1980), 508 pp. [subsequent volumes: 2 (1981), 511 pp.; 3 (1981), 499 pp.; 4 (1983), 532 pp.; 5 (1985), 476 pp.; 6 (1987), 424 pp.; 7 (1991), 439 pp.]

Cays of the Belize barrier reef and lagoon [with D. R. Stoddart and D. L. Spellman].
Atoll Research Bulletin, 256 (1982), 1-76 .

Bird and Denis Islands, Seychelles [with D. R. Stoddart].
Atoll Research Bulletin, 253 (1981), 1-76.

Topographic and floristic change, Dry Tortugas, Florida, 1904-1977 [with D. R. Stoddart].
Atoll Research Bulletin, 253 (1981), 1-76.

Cays of the Belize barrier reef and lagoon [with D. R. Stoddart and D. L. Spellman].
Atoll Research Bulletin, 256 (1982), 1-76.

Ten years of change on the Glover's Reef cays [with D. R. Stoddart and M.-H. Sachet].
Atoll Research Bulletin, 257 (1982), 1-38 .

Plants of the Belize cays [with D. R. Stoddart, M.-H. Sachet and D. L. Spellman].
Atoll Research Bulletin, 258 (1982), 1-77.

Species-area relationships on small islands: floristic data from Belizean sand cays [with D. R. Stoddart].
Smithsonian Contributions to Marine Science, 12 (1982), 527-539.

Geographical checklist of Micronesian Pteridophyta and Gymnospermae [with M.-H. Sachet and R. L. Oliver].
Micronesica, 18 (1982), 23-82.

The human factor in the biogeography of oceanic islands.
Comptes rendus sommaire des Seances de la Societe de Biogeographie de Paris, 59 (1983), 147-190.

Henderson Island (southeastern Polynesia): summary of current knowledge [with M.-H. Sachet and D. R. Stoddart].
Atoll Research Bulletin, 272 (1983), 1-47.

An ecological reconnaissance of Tetiaroa Atoll, Society Islands [with M.-H. Sachet].
Atoll Research Bulletin, 275 (1983), 1-67.

Natural history of Cousin Island.
Atoll Research Bulletin, 273 (1983), 7-38.

List of vascular flora of Agalega [with M.-H. Sachet and D. R. Stoddart].
Atoll Research Bulletin, 273 (1983), 109-142.

List of plants collected on Coetivy Island, Seychelles [with S. A. Robertson].
Atoll Research Bulletin, 273 (1983), 143-156.

List of plants collected on Platte Island, Seychelles [with S. A. Robertson].
Atoll Research Bulletin, 273 (1983), 156-164.

List of plants of Poivre Island, Amirantes [with S. A. Robertson].
Atoll Research Bulletin, 273 (1983), 165-176.

List of plants collected on Alphonse Island, Amirantes [with I. A. D. Robertson and S. A. Robertson].
Atoll Research Bulletin, 273 (1983), 177-184.

Vegetation and floristics of western Indian Ocean coral islands [with D. R. Stoddart].
Biogeography and Ecology of the Seychelles Islands, ed. D. R. Stoddart (The Hague: W. Junk) (1984), 221-238.

Phytogeographic comparison of Polynesia and Micronesia.
Bishop Museum Special Publications, 72 (1984), 33-44.

Present state of knowledge of the flora and vegetation of emergent reef surfaces.
Proceedings of the Fifth International Coral Reef Congress, 5 (1986), 107-112.

A geographical checklist of the Micronesian Monocotyledonae [with M.-H. Sachet and R. L. Oliver].
Micronesica, 20 (1987), 19-129.

Marie-Hélène Sachet: islands, atolls and reefs.
Atoll Research Bulletin, 293 (1987), 1-7.

Flora of Maupiti, Society Islands [with M.-H. Sachet].
Atoll Research Bulletin, 294 (1987), 1-70.

Flora of the Gilbert Islands, Kiribati, checklist [with M.-H. Sachet].
Atoll Research Bulletin, 295 (1987), 1-33.

Henderson Island: dedicated to S. Dillon Ripley.
Atoll Research Bulletin, 321 (1989), 1-3.

New collections and notes on the plants of Henderson, Pitcairn, Oeno, and Ducie Islands [with G. Paulay, T. Spencer and R. L. Oliver].
Atoll Research Bulletin, 329, 1-18.

A review of the natural history of the Marshall Islands.
Atoll Research Bulletin, 330 (1990), 1-100.

Plants of the reef islands of the northern Great Barrier Reef [with D. R. Stoddart].
Atoll Research Bulletin, 348 (1991), 1-82.

Phytogeography and vegetation of the reef islands of the northern Great Barrier Reef [with D. R. Stoddart].
Atoll Research Bulletin, 349 (1991), 1-19.

Plants of the Jamaican cays [with D. R. Stoddart].
Atoll Research Bulletin, 352 (1991), 1-24.

ATOLL RESEARCH BULLETIN

NO. 356.

ENVIRONMENTAL VARIABILITY AND ENVIRONMENTAL EXTREMES AS FACTORS IN THE ISLAND ECOSYSTEM

BY

D.R. STODDART AND R.P.D. WALSH

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ENVIRONMENTAL VARIABILITY AND ENVIRONMENTAL EXTREMES AS FACTORS IN THE ISLAND ECOSYSTEM

BY

D. R. STODDART[1] AND R. P. D. WALSH[2]

ABSTRACT

This paper discusses the major environmental hazards affecting island ecosystems, with varying magnitudes and on differing spatial and temporal scales. Vulcanicity and earthquakes are spatially concentrated at present, but can be devastating, especially in continental-marginal areas. Island area and elevation are subject to changes in sea level, notably on Pleistocene time scales but continuing to the present. Tsunamis are episodic sea-level disturbances which may have catastrophic effects. Of climate factors variability in rainfall has greatest ecological consequences: we examine temporal variation in annual rainfall on islands, rainfall seasonality and its variability, the magnitude and frequency of daily rainfalls, and the magnitude and frequency of droughts, using data for tropical island stations. Some perturbations are linked to the El Niño phenomenon and many show regional and temporal coherence. The most extreme climatic disturbances experienced on islands are hurricanes, which vary in frequency both spatially and temporally. This inherent environmental variability and associated extreme conditions has major consequences for the establishment and survival of plants and animals on islands, especially through the control of vegetation growth by rainfall. Ultimately these factors set thresholds for the habitability of islands by man.

---

1. Department of Geography, University of California at Berkeley, Berkeley, California 94720, U.S.A.

2. Department of Geography, University College of Swansea, Swansea, SA2 8PP, United Kingdom.

Manuscript received 15 January 1991; revised 10 December 1991

INTRODUCTION

Thirty years ago, in 1961, F. R. Fosberg convened a remarkable symposium on *Man's Place in the Island Ecosystem* at the 10th Pacific Science Congress in Honolulu. At the end of the meeting, O. H. K. Spate (1963) pointed out that much of the discussion had been concerned with scale and with change. During the Symposium the variety of physical environments in the Pacific was comprehensively outlined by William L. Thomas, Jr. (1963). His treatment of the distribution and nature of these environments still stands. In this paper, however, we carry the analysis a stage further by concentrating on spatial and temporal scales of change, and we demonstrate how, far from island environments being merely static backdrops for human activities, they are themselves continuously changing, not only on the scale of recent geological time but also on scales measured in years and decades. Our discussion concentrates on sea-level change and rainfall variability, since we judge these to be of central significance in tropical small-island ecosystems. Nunn (1990, 1991) has recently addressed issues of environmental change on Pacific islands, but since he deals with rainfall only in the context of heavy storms associated with hurricanes our treatments do not overlap. Other authors have recognised the importance of extreme or infrequent events in understanding island ecologies (Waddell 1973, 35; Lea 1973, 56; Whitmore 1974), a subject also judged of importance by McLean (1980), and we consider these phenomena as well as longer-term secular changes. For practical purposes we are concerned mainly with tropical islands, but we take our data from the Caribbean and the Indian Ocean as well as from the Pacific.

VOLCANIC ACTIVITY AND EARTHQUAKES

Many oceanic islands are of volcanic origin, and many coral atolls rest on volcanic foundations. It is not surprising therefore that many islands continue to be affected by continuing volcanicity and seismicity. Such phenomena are strongly concentrated at plate margins, and may have increased in frequency during the Quaternary (Kennett and Thunell 1975). There is also some evidence of temporal periodicities in Pacific volcanism over the past century (McLean 1980, 153).

A basic distinction can be made between the basaltic shield volcanoes of oceanic provinces (such as Hawaii, Tahiti and the Galapagos) and andesitic volcanoes of island arcs and continental borderlands, the latter built primarily by low-angle lava flows and the latter characterised by explosive release of pyroclastic materials. Island volcanoes initiate their growth by submarine activity and finally reach the surface. Of ten active volcanoes in western Tonga, for example, seven are still submarine. The ephemeral creation of new subaerial islands by the other three has frequently been observed, but

since they are built of pyroclastics they are easily eroded. Falcon Island (Funuafo'o) was 100 m high in 1885, only 50 m in 1889, down to 13 m in 1895, and had disappeared by 1898. In 1900 it was 3 m high. It appeared again in October 1927 and by spring 1928 was nearly 5 km in diameter and 100 m high; it had disappeared by 1949 (Lister 1890; Hoffmeister et al. 1929). There is a similar history for Metis Shoal (Melson et al. 1970). With continuing activity, however, land may ultimately become more permanent and then become colonised by plants and animals. Surtsey, which was formed on the Mid-Atlantic Ridge south of Iceland in 1963, has been continuously monitored since then, though its biota in such high latitudes is small (Fridriksson 1975).

Temporal and spatial periodicity in volcanicity allows the processes of colonisation, succession and extinction to be studied. Most work has been carried out on the dated individual lava flows of Hawaii (Macdonald et al. 1983), both in terrestrial habitats (e.g. MacCaughey 1917; Skottsberg 1941) and in marine, where the development of coral communities has been studied on a series of flows up to 102 years old (Grigg and Maragos 1974). Such successions can rapidly be terminated by continuing volcanic activity, most dramatically in andesitic areas. The most famous such case is the explosive destruction of Krakatau in August 1883, in an explosion heard up to 4653 km away (Self and Rampino 1981; Simkin and Fiske 1983). In the Lesser Antilles Soufrière on St Vincent exploded on 7 May 1902, followed the next day by Pelée on Martinique, 145 km to the north (Anderson and Flett 1902; Anderson 1908). Ash and mud on the latter generated a massive nuée ardente which destroyed the town of St Pierre. Subsequent activity continues to be monitored, as are the ecological consequences of such events (e.g. Howard 1962).

These can be of ocean-wide extent. Sachet (1955) documented the dispersion of pumice from the Krakatau explosion across the Indian Ocean, where on some islands it formed new beach ridges several meters in thickness. Such non-carbonate inputs are of considerable ecological interest on atolls. Likewise Richards (1958) tracked pumice from the explosion of Barcena in the Islas Revillagigedo in 1952 across the Pacific (Richards and Dietz 1966).

Even comparatively small volcanic events may have considerable ecological consequences. Dickson (1965) points out that in the case of the 1962 eruption on Tristan da Cunha, new lava flows covered 8 ha and ash fields 4 ha, but the vegetated area affected by toxic gases was 32 sq km or one quarter of the area of the island. Tristan well illustrates a conclusion drawn by Brattstrom (1963, 522) following the Barcena eruption: 'The major effect of the catastrophe may not be the event itself. Even though the event may be spectacular and destructive, the side effects or after-effects may be more critical to the survival of both individuals and species ... and to reinvasion and repopulation.' On Tristan da Cunha the explosion occurred in the area most affected by human activities. The population was evacuated from the island, leaving behind uncontrolled cattle, sheep, donkeys, geese, fowls, dogs and

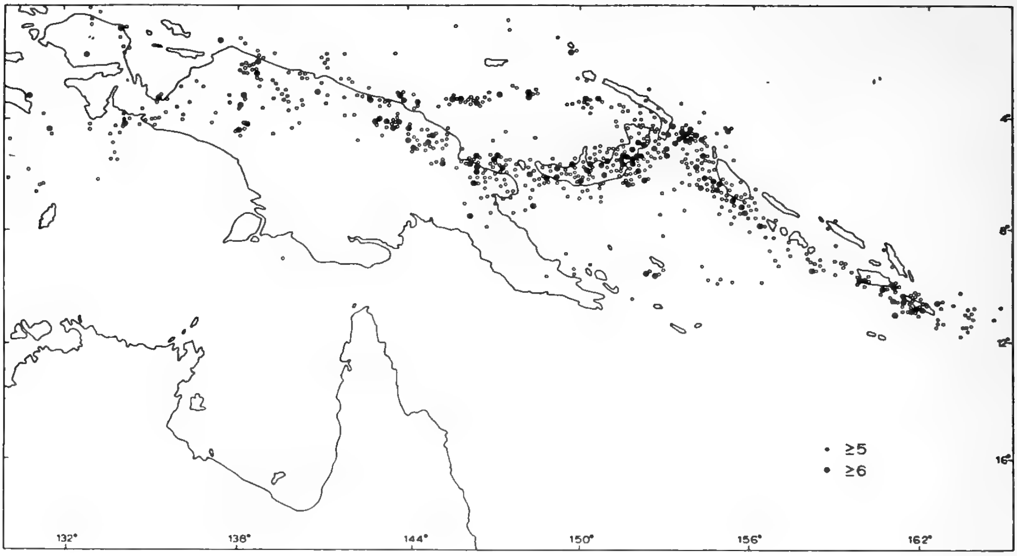


Figure 1. Distribution of earthquakes greater than M = 5 in the New Guinea-Solomon Islands area, 1958-1966 (From Denham 1969).

cats, which perpetuated and transformed the effects of the eruption itself (Dickson 1965; Baird 1965).

Seismically-generated topographic changes may have substantial impact on coastal geomorphology and ecology of islands. Thus at Punta Espinosa on Fernandina Island in the Galapagos the emersion of barnacles and corals indicates upheaval of 0.3-0.5 m between September 1974 and January 1975, and at Urvina Bay on Isabela emersed massive corals indicate uplift of ca 5 m during a few months in 1953-1954 (Glynn and Wellington 1983, 33-36, 121-122).

On the highly seismic islands of Vanuatu [New Hebrides] Taylor and his colleagues have researched episodic reef emergence for over a decade using in part the evidence of microatolls bevelled to former sea-level positions (Scoffin and Stoddart 1978). They have found emergence on North Santo of 1.2 m in 1866 and 0.6 m in 1973; on South Santo of 0.29 m in 1946 and 0.26 m in 1965; on North Malekula of 1.23 m in 1729 and 1.05 m in 1965; and on South Malekula of 0.35 m during 1957-1958 (Taylor et al. 1981, 1987, 1990). Similar upheavals have been documented elsewhere in Melanesia, for example on New Britain and Guadalcanal (Everingham 1974); Figure 1 shows the concentration of earthquakes greater than M = 5 during the short time period 1958-1966. As in the case of volcanic eruptions the effects of

earthquakes may be delayed or indirect. Thus the Madang, New Guinea, earthquake of November 1970 (M = 7) had a devastating immediate destructive effect on shallow-water corals in the neighbouring lagoon, but was followed by a lagged sediment input to coastal areas as inland rivers eroded massive landslide deposits (Stoddart 1972; Pain and Bowler 1973).

Over longer time spans episodic tectonic uplift interacting with Quaternary sea-level fluctuations has transformed island topographies in island-arc localities. The suites of uplifted coral reef terraces of eastern New Guinea are perhaps best known (Chappell 1974; Bloom et al. 1974), but similar cases are widespread and illustrate the ephemerality of topographic forms in such situations. The raised terraces of Timor and Atauro have been described by Chappell and Veeh (1978), while Pirazzoli et al. (1991) have identified reef terraces up to over 450 m high and 1 million years old on Sumba in Indonesia. Elevated reefs do exist in intra-plate situations, but there they originate through different mechanisms (McNutt and Menard 1978).

SEA-LEVEL CHANGES

Many of the islands on which volcanic or seismic events have been documented are comparatively large. Fosberg in 1961 pointed out the vulnerability of smaller islands to the effects of external environmental events. Coral atolls and indeed even many oceanic volcanic islands are small. The larger atolls have total areas of about 1000 sq km, and the largest ones (such as Kwajalein in the Marshalls) reach 2500-3000 sq km. But these are total areas bounded by peripheral reefs. The land area at high tide is much smaller. Table 1 gives the total areas and dry-land areas of a number of Pacific and Indian Ocean atolls, and the ratio of one to the other. Clearly quite small shifts in the sea-air interface will have major effects on the area of dry land. Not only will land areas on reefs vary greatly with even quite small changes in sea-level, but many now submerged banks would become land during small (ca 100 m) negative shifts in sea-level such as those associated with the last major continental glaciation. Thus the Bahama Banks at that time formed a flattopped land area totalling 155,000 sq km and the Pedro Bank south of Jamaica 7900 sq km. In the Indian Ocean the Seychelles Bank reached 43,000 sq km, Saya de Malha 40,000, Nazareth Bank 26,000, and the Chagos Banks 13,500 sq km. The southwest Indian Ocean was converted from a largely empty sea to an archipelago of large islands which could serve as stepping-stones for trans- and inter-oceanic dispersing species (Figure 2). Conversely a positive movement of sea-level, of only a few meters, would at least temporarily remove dry-land areas from most coral reefs, with concomitant general extinction of island biotas. The effects of similar sea-level changes on steeper high islands would be less spectacular, except that in continental marginal areas falls in sea-level might unite islands to form larger land masses or indeed terminate their condition of insularity altogether .

Table 1. Areas of atolls

	A Total area sq km	B Land area sq km	A/B
Marshalls:			
Taongi	107.0	3.8	28.2
Bikar	56.5	0.5	113.0
Eniwetok	1023.9	6.4	160.0
Bikini	691.5	7.3	94.7
Rongelap	1104.5	6.4	172.6
Ailinginae	152.2	3.3	46.1
Rongerik	182.2	2.1	86.8
Utirik	92.4	2.7	34.2
Taka	133.9	0.5	267.8
Ujelang	94.1	1.6	58.8
Ujae	216.3	1.6	135.2
Wotho	118.7	4.1	29.0
Lae	26.1	1.6	16.3
Kwajalein	2335.5	14.4	162.2
Likiep	466.4	9.4	49.6
Jemo	3.8	0.2	19.0
Ailuk	232.1	5.7	40.7
Wotje	773.5	8.7	88.9
Erikub	302.1	0.9	335.7
Mejit	9.1	3.4	2.7
Maloelap	1004.9	9.9	101.5
Other Pacific atolls:			
Kapingamarangi	61.6	1.1	56.0
Raroia	398.9	20.7	19.3
Rangiroa	1639.5	43.0	38.1
Indian Ocean atolls:			
Addu	131.8	11.2	11.8
Diego Garcia	170.0	30.0	5.7
Salomon	36.0	3.1	11.6
Peros Banhos	510.0	10.6	48.1
Farquhar	170.0	7.5	22.7
Cosmoledo	152.0	5.2	29.2
Aldabra	365.0	155.0	2.4
Astove	9.5	4.2	2.2

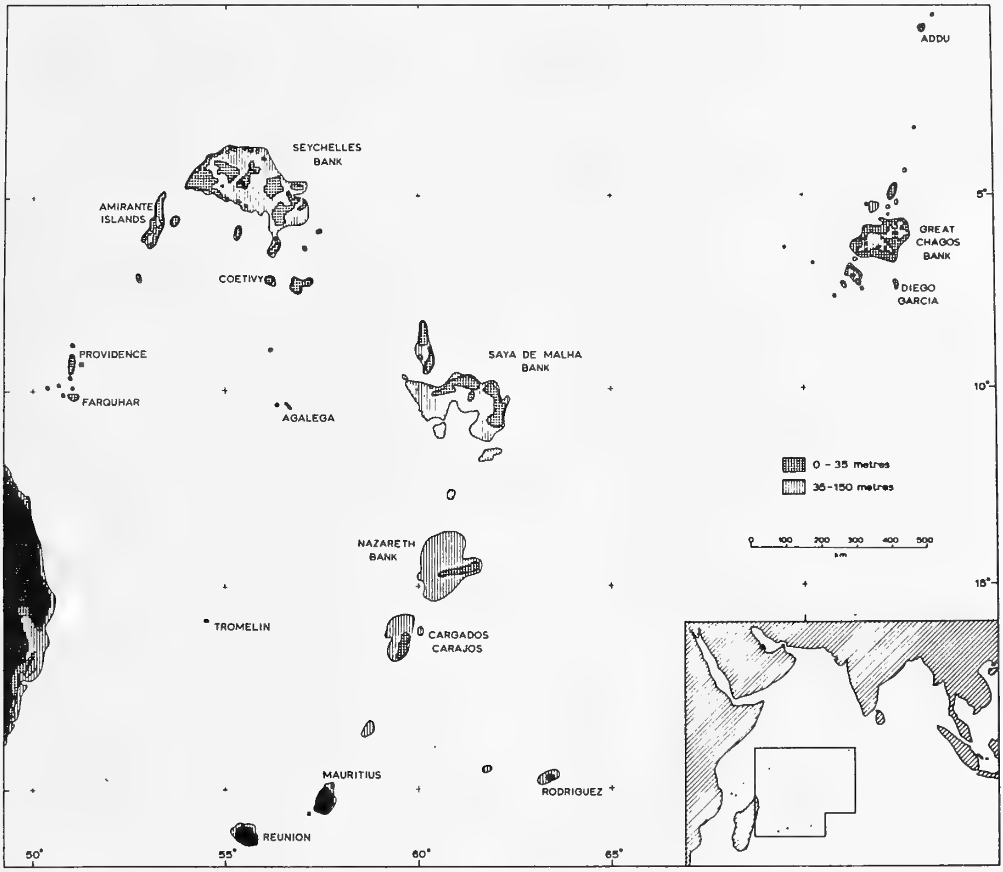


Figure 2. Land areas in the southwest Indian Ocean during the last glacial low stand of the sea (From Stoddart 1971c).

Changes of these magnitudes and consequences are of recent date and have been rapidly achieved. Sea-levels of the last glaciation were more than 100 meters below present sea-level until about 15,000 years ago. The major contribution of water back to the oceans resulted from the collapse of the 4000 km wide Laurentide ice sheet, which disappeared in about 4000 years, its margin retreating by up to 5 meters per week (Andrews 1973). Sea-level rise as a result averaged 1 meter/100 years over several thousand years to 6000 B.P. Because of differential adjustment of the crust to the new water load and also because of decantation of water from isostatically rising land, the transgression in many areas continued after this date, though at different rates in different parts of the world. Figure 3 gives a series of sea-level curves from different areas for the last few thousand years, and shows how recently

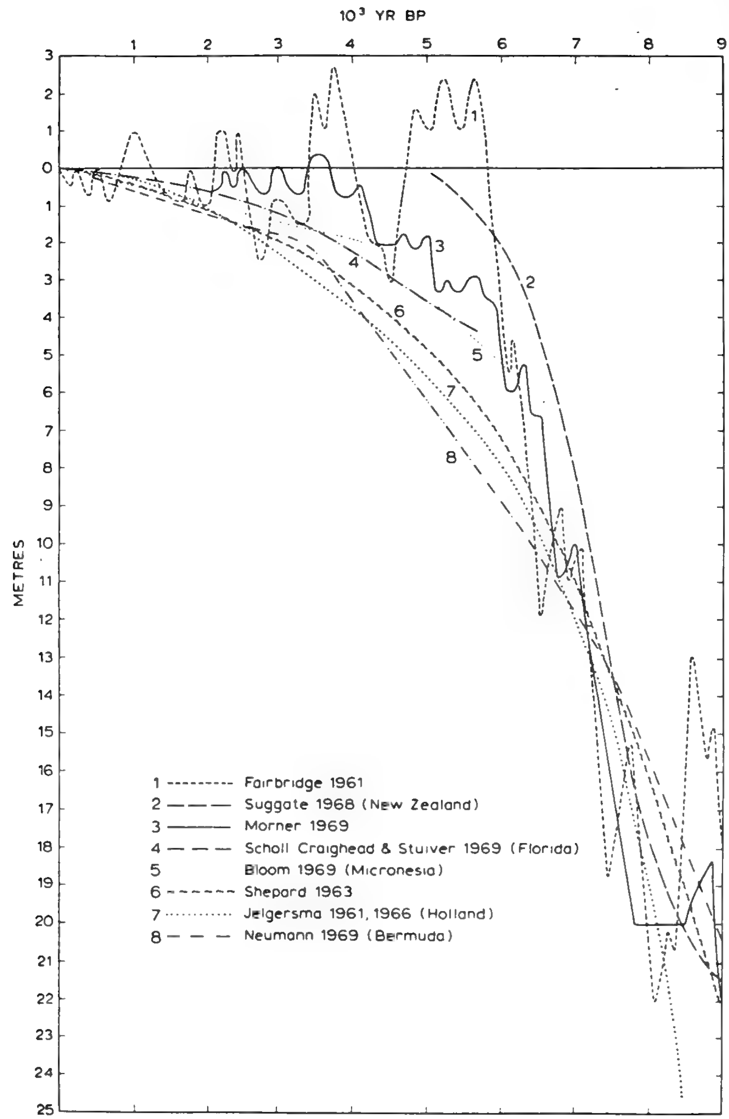


Figure 3. Rise in sea-level over the last 9000 years (From Mörner 1971).

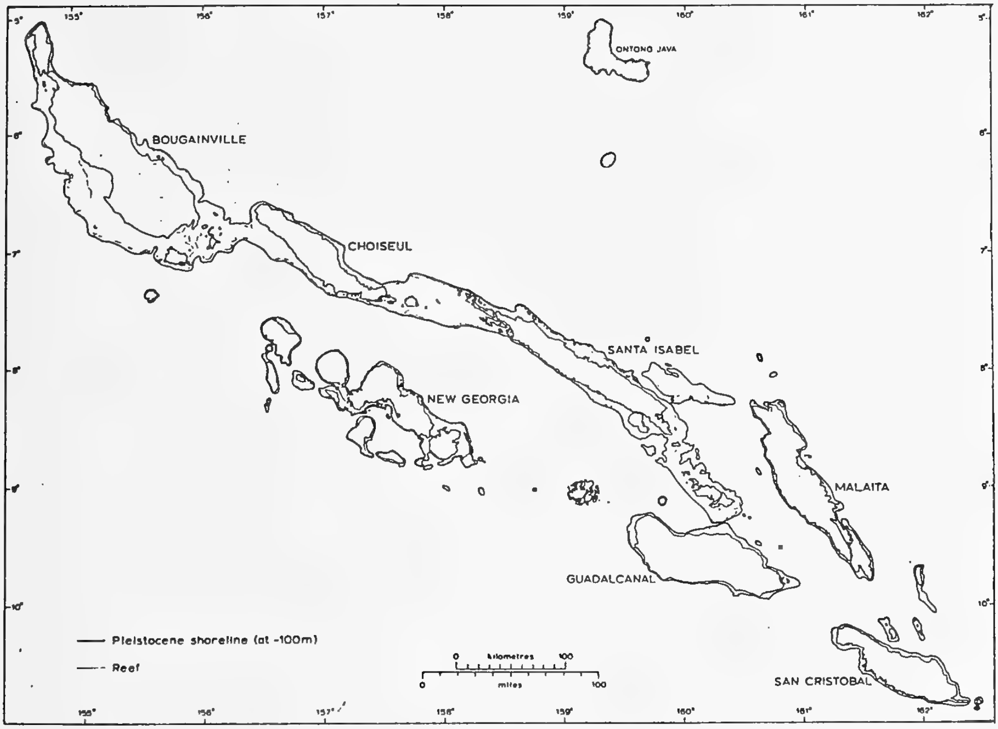


Figure 4. Topography of the Solomon Islands archipelago during the last glacial low stand of the sea and location of modern coral reefs.

the sea has risen from its glacial low level, and for how short a time (2000-3000 years, or 0.1 per cent of the length of the Pleistocene) it has stood at its present level. It is worth noting that while one almost automatically thinks of sea-level change in the vertical dimension, perhaps because of the ubiquitous convention of constructing sea-level curves such as those in Figure 3, in many shelf areas the sea transgressed horizontally across flat-lying lands now shallowly submerged, at rates of up to 10-15 meters per day (Galloway and Löffler 1972). Many modern reefs started growing 6000-7000 years ago when the sea was lower, and have been isolated from present island shores by this process of horizontal transgression; the reefs and islands of the Solomons in the southwest Pacific (Figure 4) form a dramatic example.

Recently it has become clear that since sea-level reached its approximate present level, different areas in the reef seas have had very different histories. This is well illustrated by comparison of the Holocene sea-

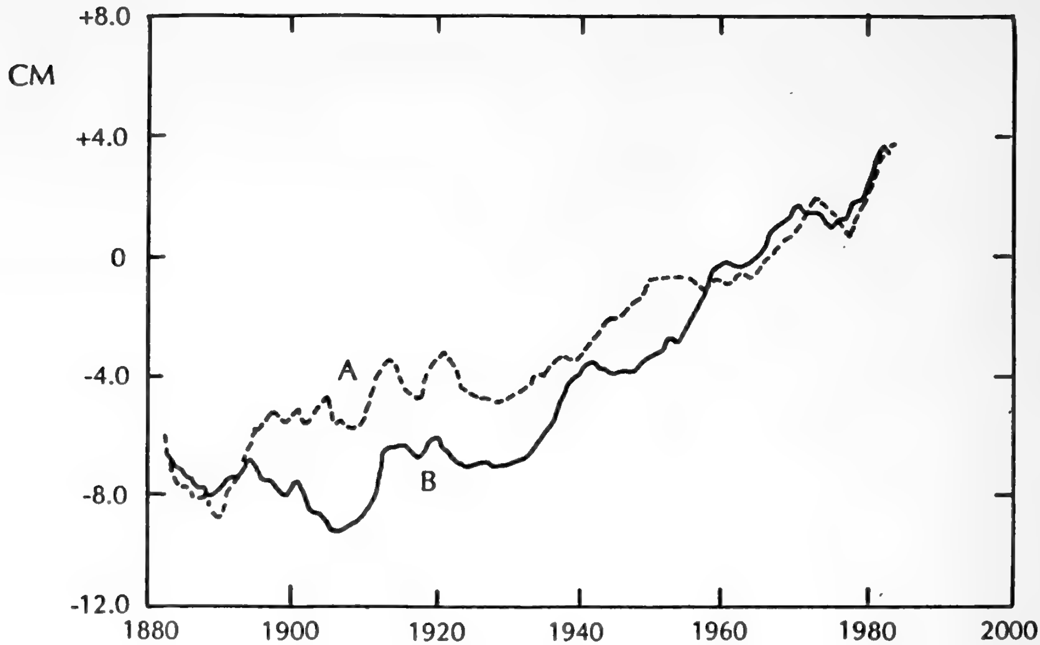


Figure 5. World rise in sea-level since 1880 from tide gauge records. Curve A based on Gornitz and Lebedeff (1987); Curve B based on Barnett (1988). Zero is taken as mean sea-level for the period 1951-1970 (From Gornitz 1991)

level curves of Chappell (1982) for the northern Great Barrier Reef and of Scholl and Stuiver (1967) and Scholl et al. (1969) for the Gulf coast of peninsular Florida. In northern Queensland, the sea reached its present level at least 6000 years ago, rose to a level 1-2 meters above the present, and then monotonically declined to its present position. In Florida, on the other hand, the sea stood 6 meters below its present level at 6000 B.P., and since then has continued to rise at a decelerating rate towards the present level. Pirazzoli and Montaggioni (1986, 1988a, 1988b) and Pirazzoli et al. (1985, 1988) identify a high stand of about 1 meter in French Polynesia between about 4000 and 1500 B.P. Similar evidence has been adduced from the Cook Islands (Woodroffe et al. 1990b), Fiji (Nunn 1990b), and the eastern Indian Ocean (Woodroffe et al. 1990a). Conversely Montaggioni (1979) found no such evidence in the Mascarenes, and this remains the case in the western Atlantic.

Several workers have calculated trends in sea-level rise on a worldwide basis over the period of instrumental tide-gauge records (Gornitz 1991; Figure 5). Thus Barnett' s examination of world tidal records for the period 1881-1980, excluding isostatically anomalous areas, showed a mean rise

of 0.14±0.01 meters per 100 years. Gornitz and Lebedeff (1987) calculated a worldwide rate of rise of 0.17 meters per 100 years. Barnett's (1984, 7982-7984) data set includes ten stations in the reef seas, including three atolls. These stations give a mean rate of rise of 0.112 meters per 100 years over the period 1901-1947. Pirazzoli (1986), using the same data sets, derived a mean rise for six reef-sea stations of 0.17 meters per 100 years , which is the same as the worldwide rate calculated by Gornitz and Lebedeff (1987). Inter-station variability is, however, considerable, reaching one-third of a meter in the case of Barnett's (1984) reef stations, and more recently Pirazzoli (1989) has reduced his estimate of sea-level rise over the past century (at least for European stations) by a factor of 2-3, to only 0.04-0.06 meters per 100 years.

Predictions of future sea-level rise over the next several decades, resulting from the 'greenhouse effect', are of the same general magnitude as that of the main postglacial transgression (Stoddart 1990). Among recent estimates Stewart et al. (1990) predict a rise of 0.6 meters by 2050, equivalent to a rate of 1 meter per 100 years, with an uncertainty of a factor of three.

In addition to secular changes, sea-level is also subject to short-period fluctuations, often associated with meteorological conditions or seismic events (see also the discussion of storm surges and tsunamis below). In the Pacific such fluctuations are strikingly correlated with El Niño-Southern Oscillation events. Over the period 1981-1983 these fluctuations had amplitudes of 55-60 cm at Jarvis, Kiritimati [Christmas] and the Galapagos Islands, and 80 cm at Nauru (Lukas et al. 1984). El Niño sea-level fluctuations at Truk have an amplitude of ca 30 cm, compared with 10 cm in non-El Niño years (Cane 1986, 51). During the 1972 event monthly mean sea-level at Guam fell 44.2 cm below mean sea level, in an area with a tidal range at springs of 1 meter. This resulted in extensive mass mortalities of emersed reef-flat organisms, particularly corals, echinoderms and molluscs (Yamaguchi 1975). Substantial fluctuations in populations of algae and sea-grasses related to periods of high and low sea-level have also been documented at Punta Galeta, Caribbean coast of Panama, by Cubit (1985), and used to speculate on the biological consequences of predicted 'greenhouse' sea-level rise. Hopley and Kinsey (1988) have suggested that coral growth could be at least temporarily accelerated as reef-flats deepen from their present frequently low-intertidal levels.

Predicted sea-level rises are also likely to have substantial physical as well as biological consequences. Thus a rising sea-level is likely to lead to erosion and landward retreat of unconsolidated beaches (Bruun 1962, 1983, 1988; Schwartz 1967), a phenomenon which would be exacerbated by increased storminess. The Ghyben-Herzberg freshwater lens on small islands would also be endangered by rising sea-levels (Buddemeier and Holladay 1977; Wheatcraft and Buddemeier 1981; Oberdorfer and Buddemeier 1988; Woodroffe 1989), and this could have profound consequences for terrestrial vegetation, water supply, and even the habitability of islands. Coastal mangrove woodlands are likely to be eroded and may locally face extinction, depending on the rate of sea-level rise (Ellison and Stoddart 1990).

In the year that the proceedings of the Honolulu symposium were published (Fosberg 1963), MacArthur and Wilson (1963, subsequently elaborated in 1967) proposed their equilibrium theory of island biogeography. This theory laid emphasis on the island attributes of distance from source of propagules and of area as factors controlling the probability of successful colonisation and subsequent survival by species in the terrestrial biota of an island. They hypothesised that the relative rates of colonization and extinction resulted in an equilibrium species number independent of the taxa present. They had but two sets of reef island data, both dealing with the distribution of vascular plants. One of these, for the individual islets of Kapingamarangi Atoll in the Carolines (Niering 1963), has been inferred by others to apply to atolls in general. These data do not in fact support the simplistic interpretation placed on them by MacArthur and Wilson (Whitehead and Jones 1969; Stoddart 1975). Their other data set from the Dry Tortugas was deeply flawed and their interpretation of it cannot be sustained (Stoddart and Fosberg 1981). We shall show later that the main controls on biotic diversity on reef islands are ecological, rather than to do with either area or location (Stoddart 1992; Williamson 1989)

Their proposals have greater relevance, however, in the case of higher islands, either elevated reef (makatea) islands or volcanic islands, for both of which area can be interpreted as a surrogate for habitat diversity. This has been well demonstrated for terrestrial arthropods, mollusca and birds in the closely-set islands of the southwest Pacific (Diamond 1972; Greenslade 1968, 1969; Peake 1969, 1971), as well as for oceanic volcanic archipelagoes (Juvik 1979).

Most workers who have considered MacArthur and Wilson's theory have considered the parameters of distance from source and island area to be invariant over time. On geological time-scales this is clearly not the case: the contrast over island life history between the leeward Hawaiian atolls (Kure, Midway), which are moving out of the reef seas, and islands such as Pitcairn, which is moving into them, has previously been noted (Stoddart 1976). It has also been suggested that the presence of endemic palms such as *Pritchardia* and other upland plants, as well as land snails and birds, on reef islands such as Laysan may be relict indicators of a complex plate-tectonic history (Schlanger and Gillett 1976; Rotondo et al. 1981). It is conceivable that the biota of the anomalously old island of Mangaia in the southern Cooks could give similar indications.

On a Pleistocene time-scale, Simpson (1974) found in the case of the Galapagos Islands that island areas and inter-island distances at the time of glacial low sea-levels gave better explanations of biotic diversity than did present conditions. Potts (1983, 1984, 1985) has made a similar case for the marine biotas of continental shelf reef localities. In the case of Aldabra Atoll, western Indian Ocean, now slightly emergent, the record of raised reef limestones shows a sequence of submergence and emergence of the atoll during the late Pleistocene, with at least two periods of total submergence and periods of low sea-level when the exposed land area reached ca 360 sq km

(Braithwaite et al. 1973). The record of one Holocene and three Pleistocene marine faunas shows repetitive colonisation and extinction consequent on changes in area, elevation and topography resulting from sea-level change, as demonstrated by Taylor's (1978) analysis of molluscan faunas. Similar effects are shown by terrestrial faunas, including crocodiles, tortoises, lizards, land birds, and molluscs (Taylor et al. 1979). Likewise in the central Pacific, Paulay (1990) has examined islands with varying degrees of tectonic uplift as a surrogate for Pleistocene sea-level change, and has shown how habitat changes resulting from differential emergence have affected marine invertebrate faunas. Such processes of extinction and colonisation in both terrestrial and marine habitats must have been universal on islands throughout the Pleistocene.

TSUNAMIS

Tsunamis are long-period (15-20 minute), long wave-length (ca 270 km) waves with small amplitude (1-2 meters) in deep water, generated seismically or volcanically principally at subduction zones and travelling across the ocean with propagation velocities of the order of 800 km/h. They are most frequent in the Pacific where most have their origin in the subduction zones off Chile and Alaska. Such long-period waves have little impact on atolls rising steeply from the deep ocean, and their effects are severely dampened by barrier reefs and within lagoons. But on shield-volcano islands such as Hawaii and the Marquesas, especially with deep embayments, tsunamis may cause serious coastal inundation. 14 tsunamis have been recorded in the Hawaiian Islands since 1830, of which six have been serious and one (that of 1 April 1946) disastrous. This latter locally raised sea-level at Hilo, Hawaii, 16.8 meters (Shepard et al. 1950) and by 10 meters in the Marquesas. By contrast the same event raised sea-level at Rangiroa and Hao Atolls in the Tuamotus by 2.2-2.3 meters above mean sea-level (the reef flats stand at ±0.3 meters). Another major tsunami occurred on 22 May 1960, giving similar elevations in Hawaii (Eaton et al. 1961; Cox and Mink 1963), much reduced inundations at Rarotonga, Samoa and in French Polynesia (Keys 1963; Vitousek 1963), and negligible effects on atolls. 121 tsunamis have been recorded at Hawaii since 1837. These included one of 6 meters in 1837, 9.1 meters in 1869 and 1896, 6.1 meters in 1923, 6.5 meters in 1933, 16.8 meters in 1946, 10.4 meters in 1952, 16 meters in 1957, and 10.5 meters in 1960 (these are maximum elevations and usually local; island-wide inundations were much less). The effects of such tsunamis are primarily economic and social, though Bourrouilh-Le Jan and Talandier (1985) have suggested that the mega-blocks on the southwestern reef flats at Rangiroa Atoll, Tuamotus, which are usually attributed to hurricanes, may be tsunami-generated.

The most extreme tsunami-type effects appear to be locally generated rather than trans-oceanic in origin (Latter 1981). The best documented is that

which impacted Ishigaki in the southern Ryukyus in 1771, following a seismic event 40 kilometers to the south-south-east. This produced the world's highest tsunami wave, reaching a maximum of 85.4 meters, and lodging large coral blocks at Ohama on the southeast side of the island (Miyagi et al. 1980, 84, 88). Moore and Moore (1984) have proposed that limestone blocks at up to 325 meters on the island of Lanai, Hawaii, have a similar origin. The tsunami generated by the 1883 explosion of Krakatau caused local inundation up to 50 meters on Java and Sumatra and killed 36,000 people (Bullard 1962; Latter 1981).

PATTERNS IN RAINFALL

After location and morphology, climate is probably the single most important factor influencing island ecology and habitability. Of the climatic elements rainfall is the most significant, the most variable, and the best documented (Brookfield and Hart 1966; Taylor 1973; Stoddart 1971a), though one should beware of inferring the uniformity of even low atoll rainfall regimes from single-station records (Stoddart 1983). Thomas (1963) outlined the spatial variations in mean annual rainfall over the Pacific Ocean (Figure 6 gives a revised rainfall map of part of the central south Pacific) and similar maps are available for the Indian Ocean (Figure 7).

The wettest atolls, such as Jaluit, Palmyra and Funafuti in the Pacific and Peros Banhos in the Indian Ocean have mean annual rainfalls of about 4 meters: the heaviest recorded atoll rainfall occurred at Funafuti, with 6.7 meters in 1940. The driest atolls, such as Wake and Canton, may have 0.5 meters or less (Table 2). High-island stations, such as Vanikoro, Pohnpei [Ponape] and Kosrae [Kusaie], have annual means over 5 meters, though in mountainous situations the rainfall may be considerably more. Many island groups, such as the Line Islands, the Marshalls and the Gilbert Islands, and the Chagos-Maldives-Laccadives chain, show pronounced latitudinal gradients in rainfall from very wet to very dry over quite short distances.

The gradient from Wake through the Marshalls and Gilberts to Tuvalu [the Ellice Islands] at 165-175° East longitude, is among the best known (Figure 8), and that from Johnston through the Lines, Phoenix and Cook Islands is comparable (Figure 9). This situation is made more interesting because here Fosberg (1954) has defined a series of latitudinal vegetation zones ('Fosberg zones') delimited by magnitudes of mean annual rainfall. Annual means form a crude index of rainfall input, however, and hence we concentrate on identifying some of the more important components of variability in rainfall patterns, using data from those atolls and high islands in the tropical seas where long records are available.

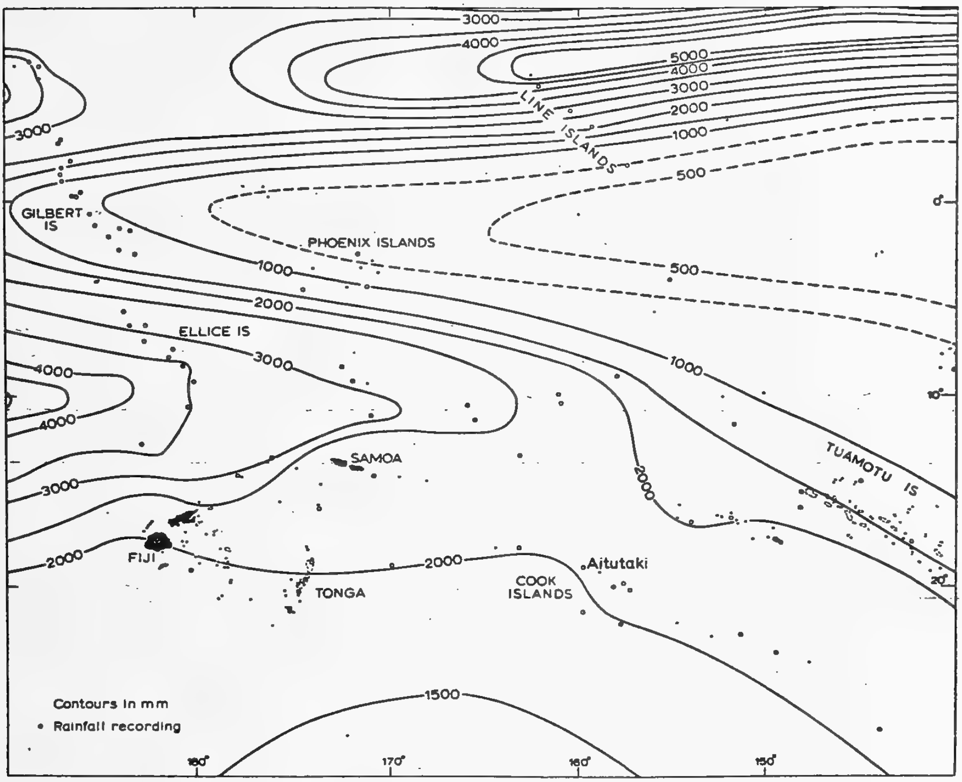


Figure 6. Distribution of mean annual rainfall (mm) in the central South Pacific Ocean.

Temporal variation in annual rainfall

Ten- and twenty-year moving averages reveal significant periodicities in many island records. These have been calculated for 7 Pacific, 6 Indian Ocean, and 7 West Indian stations. Figures 10, 11 and 12 give sample time series for Apia, Samoa; Mahe, Seychelles; and stations on Dominica, Barbados and Trinidad. Tables 3, 4 and 5 quantify the main temporal variations for 3 Pacific, 6 Indian Ocean, and 4 West Indian stations.

In the West Indies the analyses suggest the existence of four rainfall 'epochs' during the last 100 years:

Late 19th century	Pre-1898	Very wet
Early 20th century	1899-1928	Relatively dry
Mid 20th century	1929-1958	Relatively wet
Recent	1959-1989	Very dry

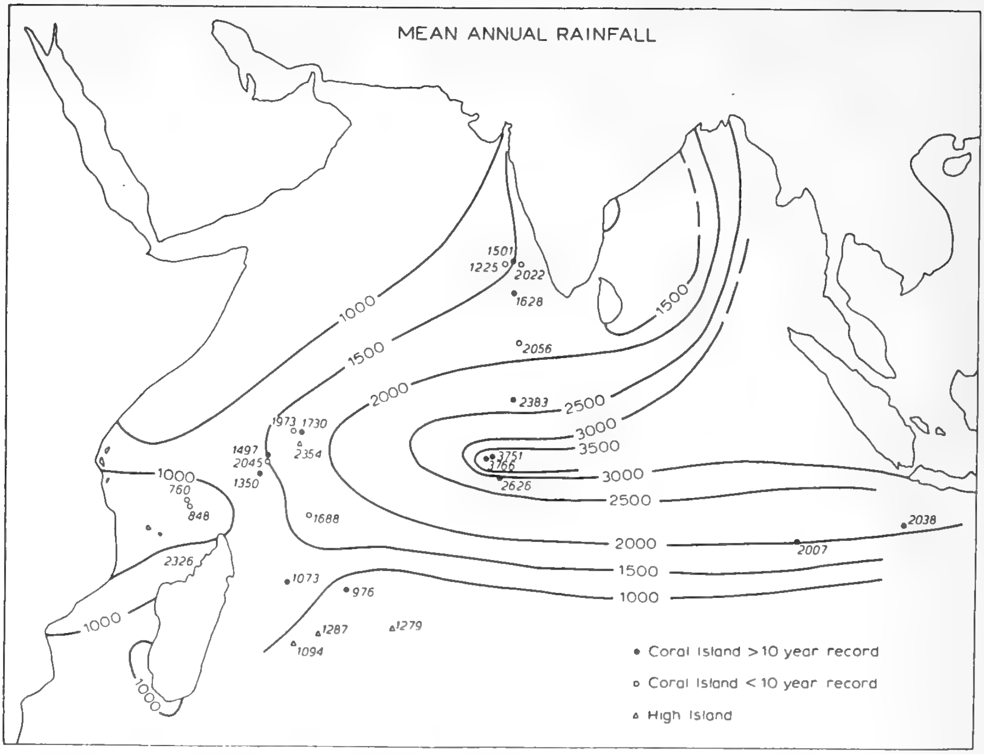


Figure 7. Distribution of mean annual rainfall over the Indian Ocean from coral island data (From Stoddart 1971a).

The magnitude of changes between these periods is substantial: in Barbados, Dominica and Guyana, stations have present-day mean annual rainfalls of 384, 296 and 610 mm (15, 12 and 24 inches) less than means in the late nineteenth century. Kraus (1955) has documented similar periodicities in eastern Australian and eastern North American stations It is interesting to note that Trinidad has recently shown a return to wetter conditions in contrast to the continued very dry conditions in the more northerly islands of Barbados and Dominica.

In the Pacific records are generally too short for all the epochs to be demonstrated, but good records for Fiji, Western Samoa and Rarotonga suggest a pattern of:

Early 20th century	Very dry
1920-1930	High rainfall
1940-present	Intermediate rainfall

Table 2. Mean annual rainfalls of sample atolls

Jaluit	4033 mm
Peros Banhos	3999
Palmyra	3810
Majuro	3048
Lamotrek	2645
Diego Garcia	2599
Kwajalein	2032
Mopelia	1854
Tarawa	1626
Rangiroa	1473
Eniwetok	1346
Aldabra	1000
Onotoa	980
Hull	838
Wake	610
Canton	432

Again the magnitudes of the differences between these periods are substantial. The 1906-1941 mean for Suva, Viti Levu, was 711 mm (28 inches) greater than that for 1883-1905; for Apia, Western Samoa, the 1920-1939 mean was 406 mm (16 inches) greater than that before 1920. Similarly in the Indian Ocean the record for Mahe, Seychelles, shows striking changes over the past century:

1891-1904	Very wet
1905-1922	Less wet
1923-1937	Very wet
1938-1954	Considerably less wet
1955-1968	Very wet
1969-1989	Less wet

The annual rainfalls in less wet periods were 500-700 mm lower than in the wetter periods (Walsh 1984).The ten- and twenty-year moving averages thus identify substantial secular changes. For present purposes it is sufficient to establish that they exist: we are not concerned to determine causes or even to establish synchroneity. Indeed, not all islands show variations of such magnitude and phase (Honolulu, Hawaii, for example, does not), though they

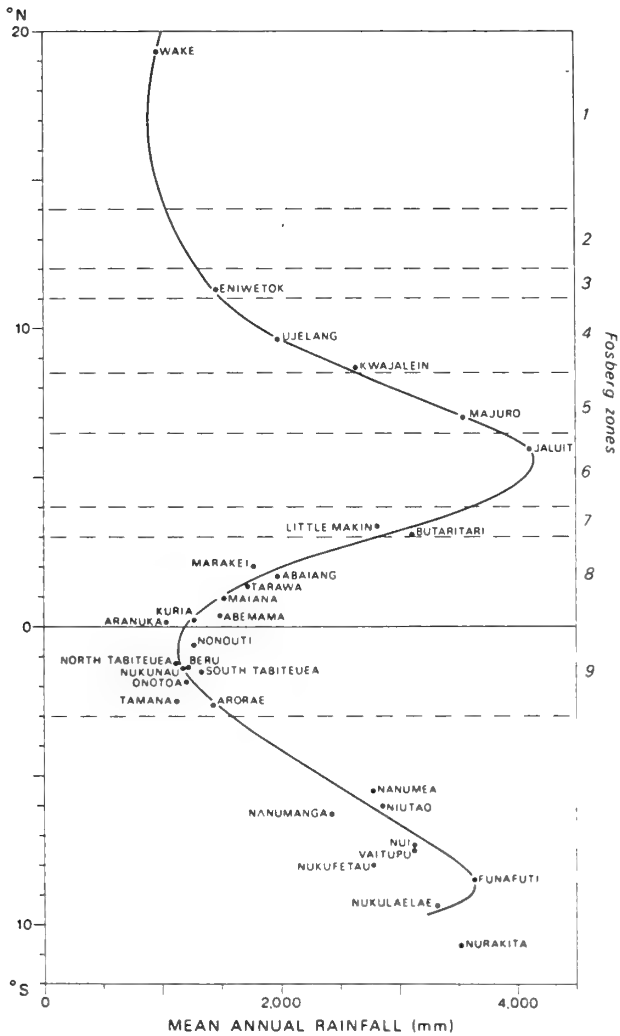


Figure 8. Latitudinal variation in mean annual rainfall in the Marshall Islands, Gilbert Islands and Tuvalu (revised from Fosberg 1956 using data in Taylor 1973).

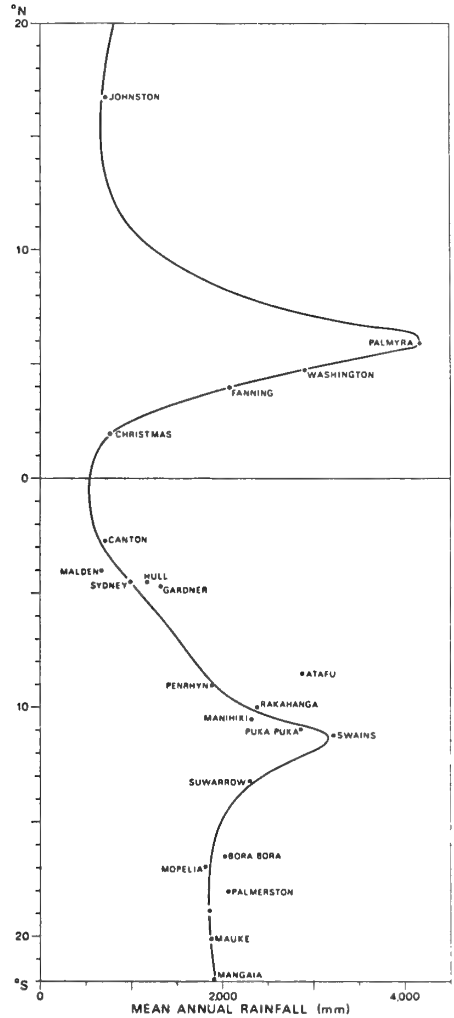


Figure 9. Latitudinal variation in mean annual rainfall from Johnston Island to the Line Islands, Phoenix Islands and Cook Islands (based on data in Taylor 1973 and later records).

Table 3. Changes in Pacific Ocean rainfalls

Station	Territory	Period of Record	Mean annual rainfall, mm				
			1883–1905	1906–1941	Change (%)	1942–1969	Change (%)
Suva	Fiji	1883–1969	2624	3348	+724 (27.59)	2945	-403 (12.04)
			1890–1919	1920–1939	Change (%)	1940–1971	Change (%)
Apia	Samoa	1890–1971	2718	3132	+414 (15.23)	2070	-262 (8.37)
			1899–1905	1906–1939	Change (%)	1940–1971	Change (%)
Rarotonga	Cooks	1899–1971	1872	2161	+289 (15.44)	2002	-159 (7.36)

Table 4. Changes in Indian Ocean rainfalls

Station	Territory	Period of record	Mean annual rainfall, mm						
			–1906	1907–1928	Change (%)	1929–1958	Change (%)	1959–1974	Change (%)
Amini Divi	Laccadives	1889, 1892-1974	1339	1513	+ 13.1%	1506	- 0.5	1573	+ 4.4
Minicoy	Maldives	1891-1974	1606	1676	+ 4.36	1566	- 6.56	1747	+ 11.56
Mahe	Seychelles	1891-1974	2575	2361	- 8.31	2224	- 5.80	2528	+ 13.67
Zanzibar	Zanzibar	1892-1950	1634	1424	- 12.85	–	–	–	–
Royal Alfred	Mauritius	1875-1974	1214	1306	+ 7.58	1313	+ 0.54	1349	+ 2.74
Tananarive	Madagascar	1890-1974	1396	1312	- 6.02	1278	- 2.59	1331	+ 4.15

Table 5. Temporal changes in West Indian rainfalls

Station	Territory	Period of record	Mean annual rainfall, mm						
			Before 1898	1899–1928	Change, mm(%)	1929–1958	Change, mm(%)	1959–1989	Change, mm(%)
Roseau	Dominica	1865-1989	2114	1874	- 240 (11.35)	2037	+ 165 (+ 8.80)	1820	- 217 (- 10.65)
Bridgetown/ Grantley Adams Airport	Barbados	1853-1988	1491	1207	- 284 (-19.05)	1376	+ 169 (+ 14.00)	1107	- 259 (- 18.82)
Port of Spain	Trinidad	1862-1968	1701	1507	- 194 (-11.41)	1666	+ 160 (+ 10.62)	1592	- 74 (- 4.44)
Georgetown	Guyana	1886-1972	2601	2237	364 (-13.99)	2414	178 (+ 7.96)	1969	- 446 (- 18.48)

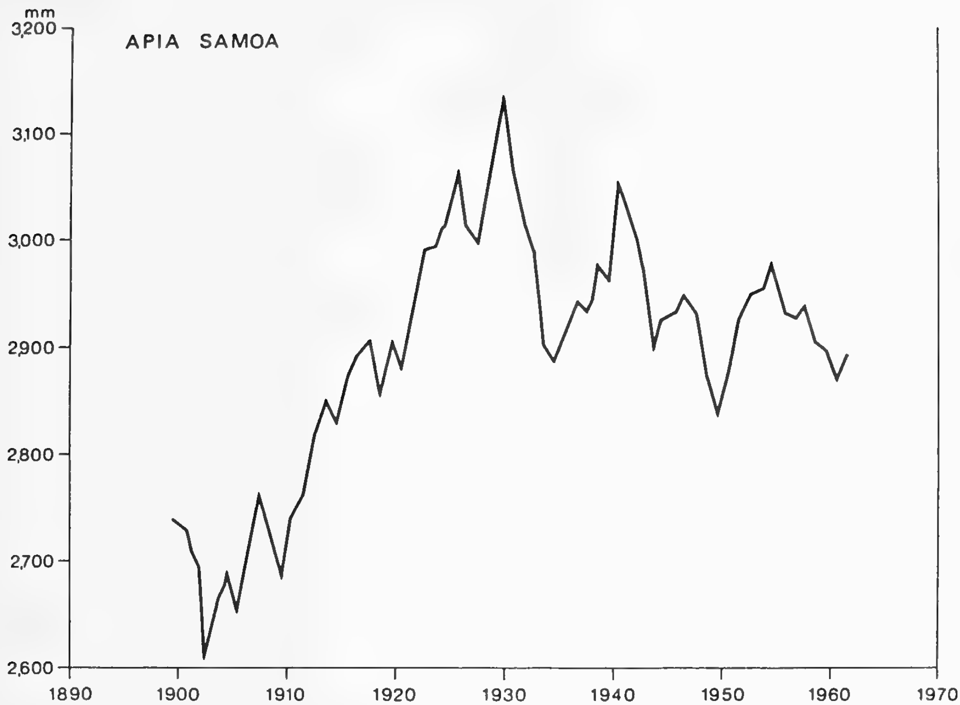


Figure 10. Twenty-year running means of annual rainfall at Apia, Western Samoa.

do seem to be characteristic of many tropical high and low islands over the last century. Where similar fluctuations have been identified in continental areas, however, it has often been shown that there are substantial spatial variations in the trends revealed (Stewart 1973; Parthasarathy and Dhar 1974).

Higher-frequency variations have also been identified using power spectrum analysis on records for 5 Caribbean and 10 Pacific Ocean islands with records ranging in length from 37 years (Banaba) to 116 years (Barbados). In the Caribbean the main cycles identified are long-term (more than 44 years), thus confirming the conclusions from the moving-average analysis; but cycles of 4.5, 5.5 and 7 years are also statistically significant. In the Pacific stations the 5.3 year cycle is particularly strong, though stations with longer records, such as Willis (in the Coral Sea), Fanning (Line Islands) and Funafuti, show significant cycles in the range 12-30 years.

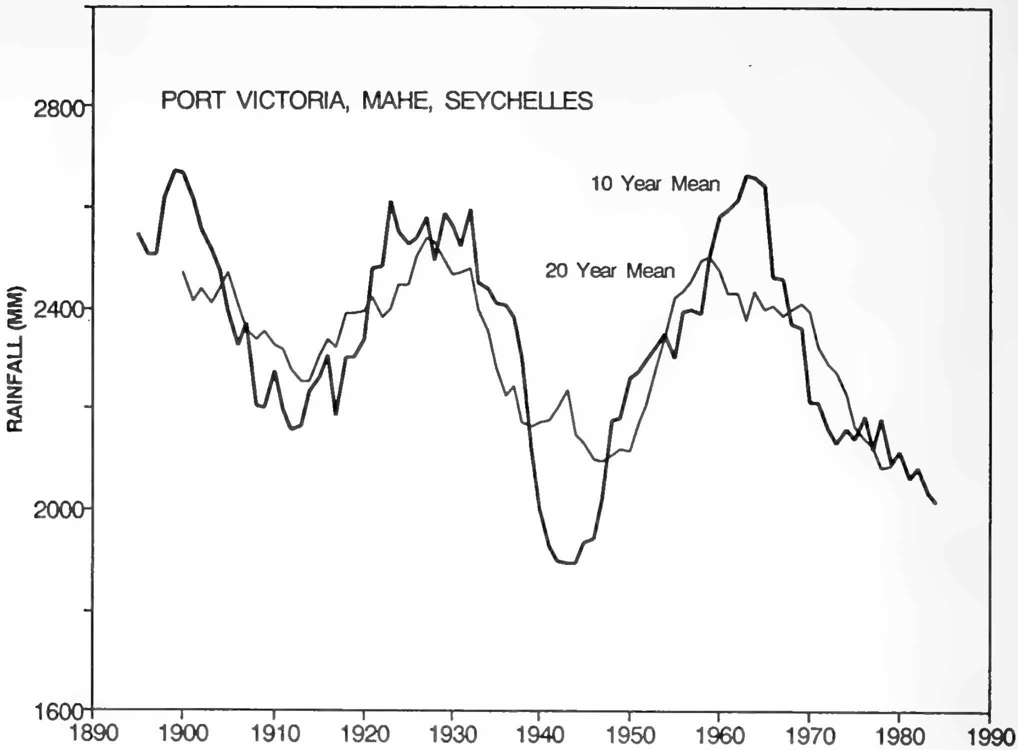


Figure 11. Ten- and twenty-year running means of annual rainfall at Port Victoria, Mahe, Seychelles.

Short-period high-magnitude fluctuations are also of great importance in some areas, notably in the Pacific equatorial islands, where they are associated with the El Niño phenomenon of coastal Peru. Figure 13 gives monthly rainfalls for the period 1942-1972 for Canton, Hull, Sydney and Gardner Atolls in the Phoenix Islands, which show highly coherent patterns. Periods of substantial rainfall (e.g. early 1953, early 1958, late 1965) are separated by long dry periods, and the variations are not only concurrent throughout the group but occur generally in the central and eastern Pacific equatorial area, including the southern Gilberts and the southern Line Islands. Figure 14 plots the spatial distribution of annual rainfall over this area for a very dry year (1968) and a very wet year (1958). In a dry year rainfall along the equator may be only a quarter of the long-term mean, whereas in a wet year it may be twice as much.

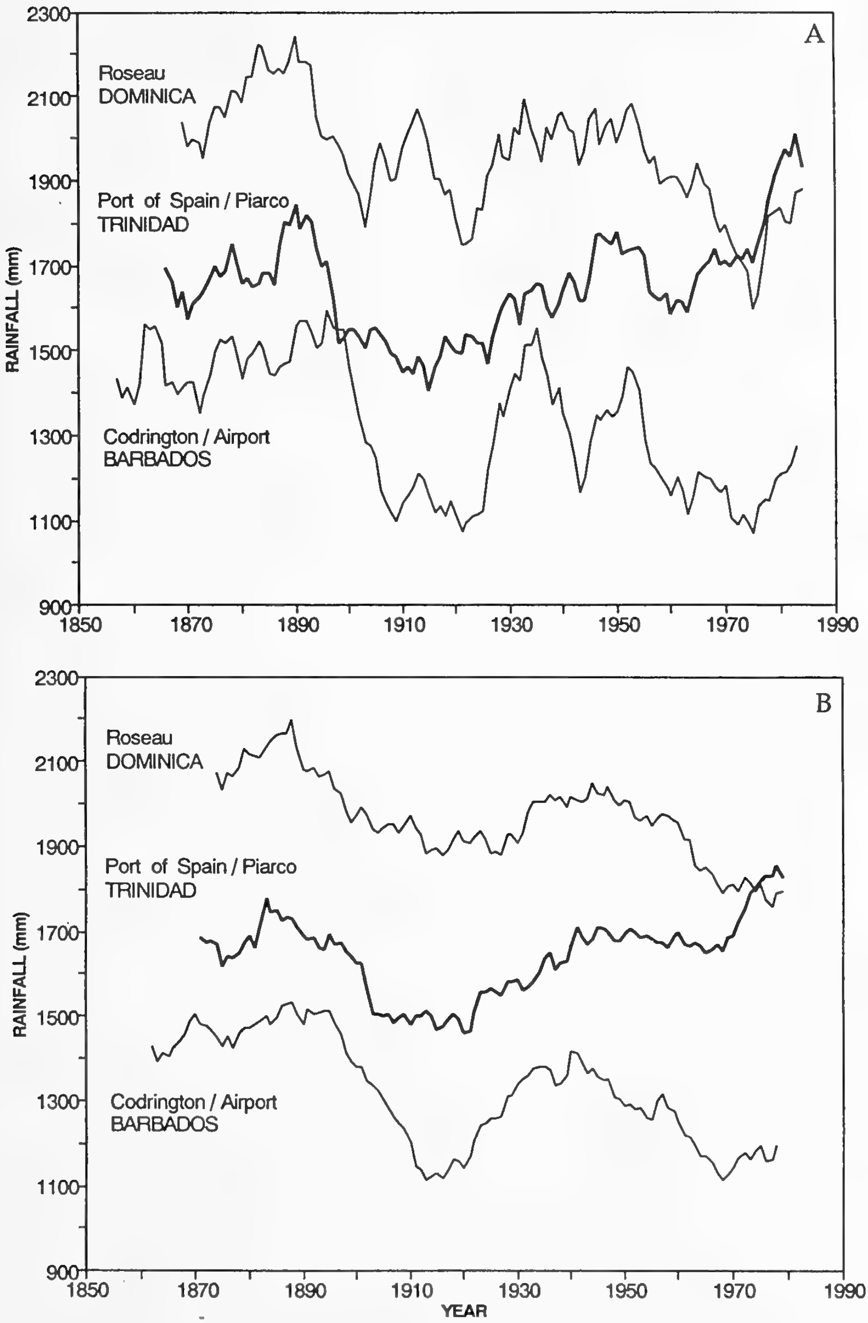


Figure 12. (A) Ten- and (B) twenty-year running means of annual rainfall at Roseau, Dominica; Port of Spain/Piarco, Trinidad; and Codrington/airport, Barbados.

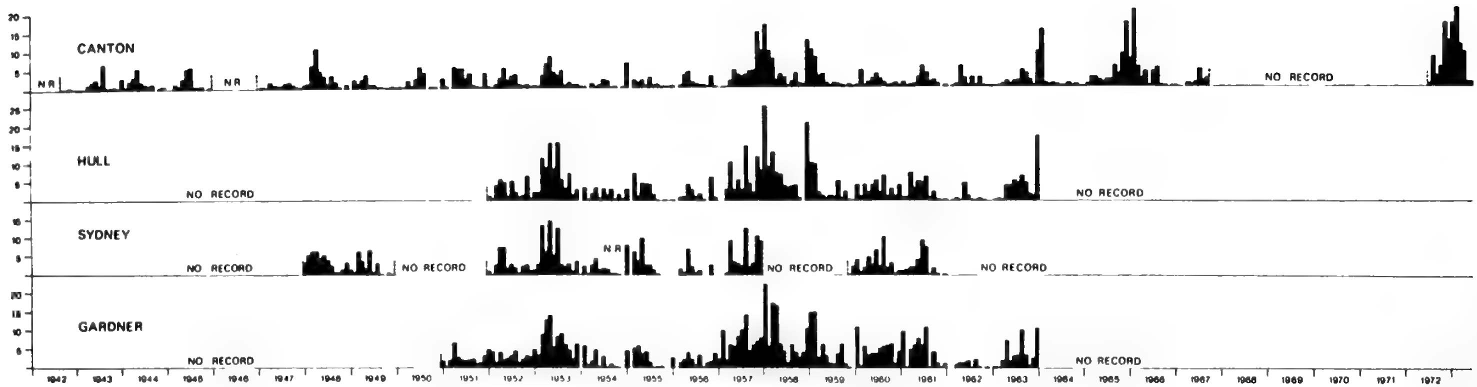


Figure 13. Variations in monthly rainfall at Canton, Hull, Sydney and Gardner Atolls, Phoenix Islands, 1942-1972.

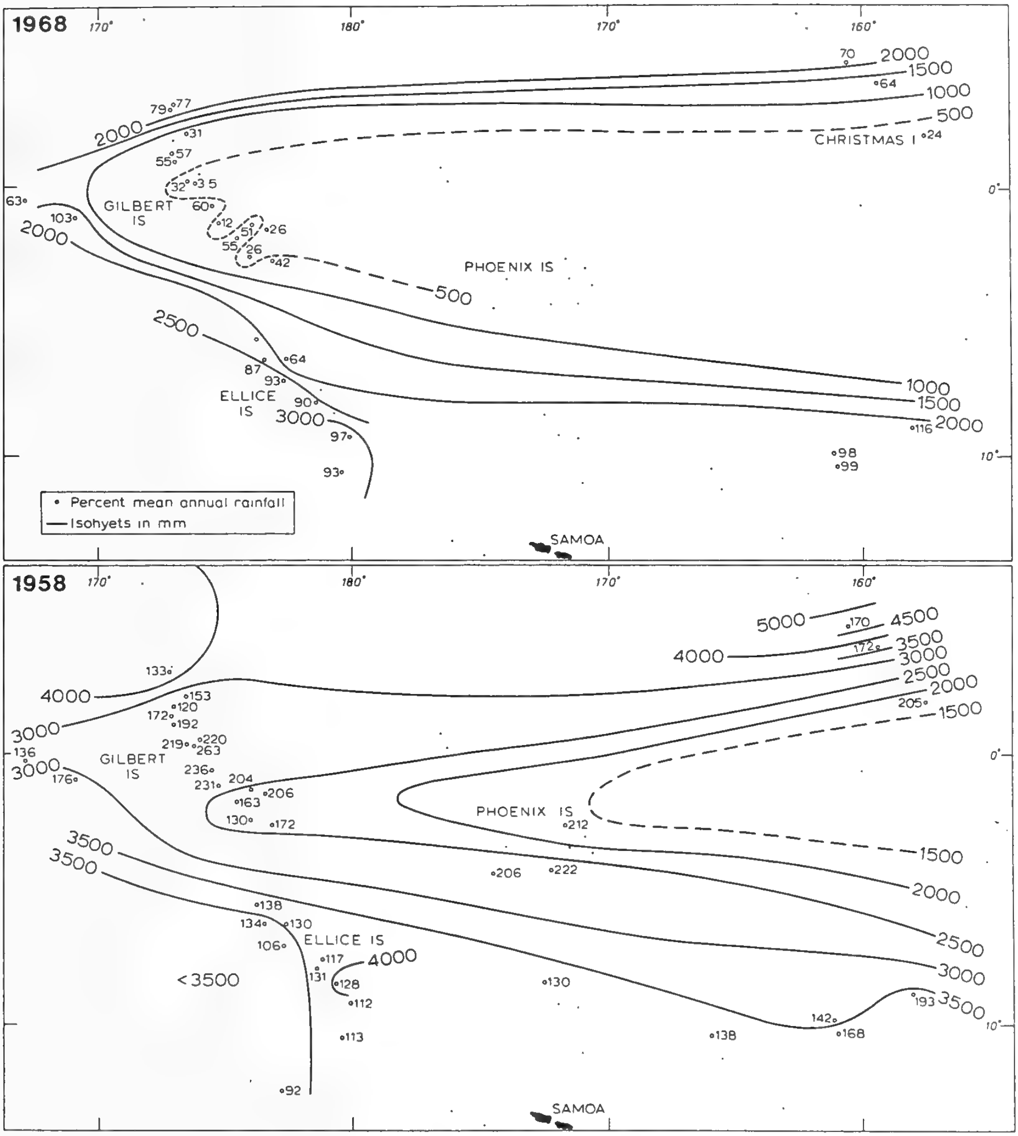


Figure 14. Rainfall distribution in the central equatorial Pacific in a dry (1968) and a wet (1958) year.

Table 6. Range of rainfall in the Southern Gilberts

Data for 1933, 1934, 1937-38, 1944-51 and 1953-69

Atoll	Wet Year 1940	Dry Year 1950	Ratio wet/dry
Little Makin	2811	1277	2.20
Butaritari	3946	1444	2.73
Marakei	3851	503	7.65
Abaiang	3555	316	11.26
Tarawa	3260	390	8.36
Maiana	3252	254	12.81
Abemama	3259	195	16.69
Kuria	2744	192	14.27
Aranuka	2836	149	19.02
Nonouti	2924	164	17.82
Tabiteuea	3275	190	17.26
Beru	3567	248	14.37
Nikunau	3763	162	23.19
Onotoa	3948	168	23.55
Tamana	3286	301	10.91
Arorae	3255	290	11.21

Data: Sachet (1957), and subsequent meteorological records.

Table 6 illustrates the magnitude of rainfall variations between events and how they increase from north to south in the Gilberts: note that on Nikunau a wet year (1940) brought 3759 mm (148 inches) compared with only 163 mm (6.4 inches) in the dry year of 1950. Extremes of these magnitudes are of obvious importance for atoll populations, more so than, for example, the predictable seasonal absolute droughts associated with monsoonal conditions on such atolls as Amini Divi, Lakshadweep (Laccadive Islands). Unpredictable droughts undoubtedly caused the abandonment of agricultural colonisation schemes on Sydney, Hull and Gardner Atolls in the Phoenix Islands, begun in 1938-1940 but abandoned during 1955-1963 (Knudson 1964). Two islands in this equatorial area (Banaba and Fanning) have rainfall records sufficiently long for power spectrum analysis: the most frequent cycles in both cases are short-term (3.6-3.7, 5.4-6.0 and 8.8-9.0 years).

The phenomena associated with these variations are reasonably well known (Ichiye and Petersen 1963; Bjerknes 1969; Rasmusson 1985; Cane 1986; Philander 1989, 1990), even though their causes are still not wholly understood. In normal years upwelling along the equator, extending westwards from the coast of South America, brings cool, nutrient-rich waters to the surface, and these support a zone of high productivity in the sea, forming the basis of the old 'On the Line' whale fishery, and also supporting large seabird colonies and guano deposition on equatorial islands. Under these conditions rainfall is low. But from time to time the upwelling is suppressed (Figure 15), sea temperatures rise 2-3°C in the central equatorial Pacific, and when the surface waters are warmer than the overlying air, instability occurs with consequent heavy rainfalls. Ocean productivity is severely reduced (Barber and Chavez 1983, 1986). During these periods seabirds populations suffer catastrophic reductions during the major 1982-1983 event all 18 breeding species of seabirds at Kiritimati, Line Islands suffered reproductive failure. The population of 10-12 million Sooty Terns *Sterna fuscata* disappeared and that of 8000 Great Frigate birds *Fregata minor* was reduced to less than 100 (Schreiber and Schreiber 1984, 1989). This resulted partly from lack of food but also because growth of land vegetation reduces nesting sites for ground-nesting seabirds and makes it difficult for larger birds such as boobies to become airborne. Similar effects were documented in the Galapagos for seabirds, marine mammals, marine iguanas, penguins, flightless cormorants and landbirds (Valle et al. 1987).

The spatial extent and temporal duration of the equatorial upwelling is thus a fundamental control of island environment over an area extending from the coast of South America (where the El Niño phenomenon was first recognised) westwards along the equator to the Caroline Islands. When upwelling is marked, islands experience droughts, land vegetation is sparse, and seabird colonies abundant, at least on undisturbed islands. When upwelling is suppressed, heavy rains occur, vegetation growth accelerates, and seabird colonies are much reduced. It follows that the input of phosphate to island soils through guano deposition is likewise episodic and correlated with El Niño events (Stoddart and Scoffin 1983).

The occurrence of historical El Niño events has been catalogued by Quinn et al. (1987) since the beginning of the sixteenth century (revising the earlier listing by Quinn et al. 1978). 47 'strong' or 'very strong' events are recorded between 1525 and 1983, with a mean periodicity of 9.9 years, and 32 'moderate' events between 1806 and 1987. Between 1803 and 1987 the mean time between moderate or stronger El Niños was ca 3.8 years. Major events occurred in 1578, 1728, 1791, 1828, 1877-78, 1891, 1925-26 and 1982-83, the last being one of the strongest recorded and certainly the best documented (Rasmusson 1983; Caviedes 1984; Gill and Rasmusson 1983; Glynn, ed. 1990; Hansen 1990; Barker and Chavez 1983, 1986).

Some of the consequences of El Niño events for the terrestrial ecology of equatorial islands have already been noted. In addition there is evidence that increased sea-surface temperatures during these events lead to thermal

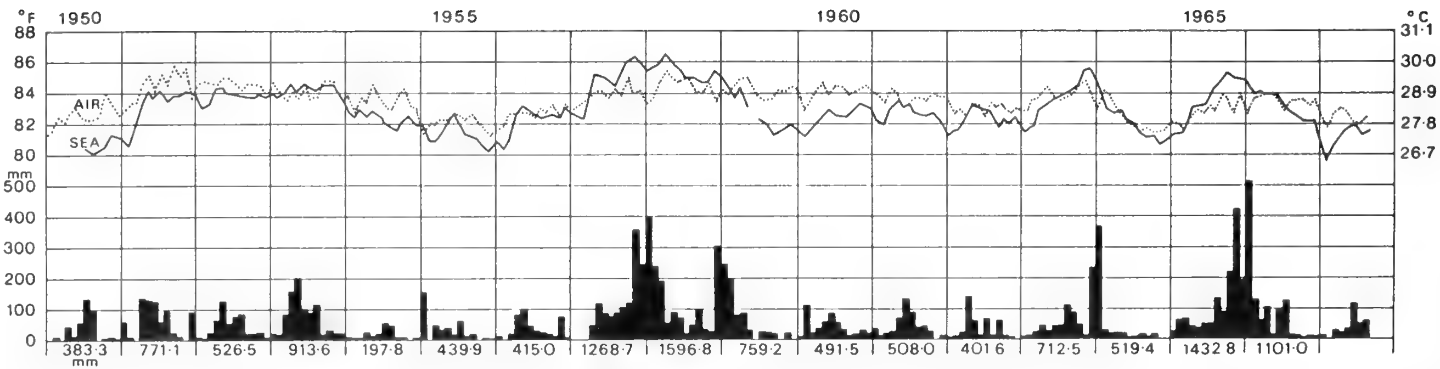


Figure 15. Relationships between monthly sea and air temperatures and monthly precipitation at Canton Island, Phoenix Islands (From Bjerknes 1969).

stress in corals and to widespread coral bleaching (Williams et al. 1987; Brown, ed. 1990; Cook et al. 1990; Glynn 1990; Rougerie 1991). Nor are El Niño effects limited to the area of Pacific equatorial upwelling: there is abundant evidence of global climatic and ecological response to these events (e.g. Duffy 1990).

Rainfall regime and seasonality

Changes in rainfall annual totals must clearly represent the sum of changes in monthly totals. Unless all monthly figures change proportionately there must also be changes in the seasonal distribution of rainfall. The nature of such changes has been analysed for Dominica, Minicoy (Lakshadweep), Viti Levu (Fiji) and Western Samoa (Figure 16). In the case of Suva, Viti Levu, changes in annual totals result mainly from changes in the rainfalls of only five months of the year, and especially in those for December, May and August; rainfall of the other seven months shows no significant changes over the period of record. In the case of Dominica, the high annual rainfalls of the wet periods results from the occurrence of a secondary maximum in November; this does not occur during dry years, when there is a single July maximum. In Western Samoa, the change from a low to a high rainfall period has resulted from increased rainfall in the wet months (October-January), i.e. the rainfall distribution became more seasonal. But the later change from wet to dry conditions involved not only a reduction in wet-season rainfall, but also an increase in dry-season amounts. At Minicoy in the Indian Ocean there was until 1958 a double peak in monthly rainfall (the main maximum in June and a secondary maximum in October), but during 1959-1974, when rainfall was about 8 per cent higher than in earlier decades, this double peak was replaced by a single maximum in July. This single peak during the wetter years also resulted in the occurrence of longer droughts in the dry season, in spite of the higher annual totals. Rainfall seasonality, which is of obvious importance in terms of geomorphic processes and vegetation growth as well as human activities, is thus related to annual totals in very complex ways. Some of the implications of changing seasonality are discussed later in this paper.

Magnitude and frequency of daily rainfalls

Of great importance, both in land erosion studies and in the ecology of nearshore areas subject to river discharge, is the frequency of high-magnitude and intensity rainfalls, which can be approached through the study of daily (or more frequent) rainfall records. Tropical islands, especially mountainous islands in trade-wind or monsoonal areas subject to hurricanes, may experience catastrophically high short-period rainfalls. Thus in 1911 Baguio on Luzon, Philippines, recorded a 24-hour rainfall of 1168 mm (3.8 feet), and in 1952 a station on Réunion, Mascarenes, recorded the world record 24-hour rainfall of 1870 mm (6.14 feet). Less extreme 24 hour maxima can also be of

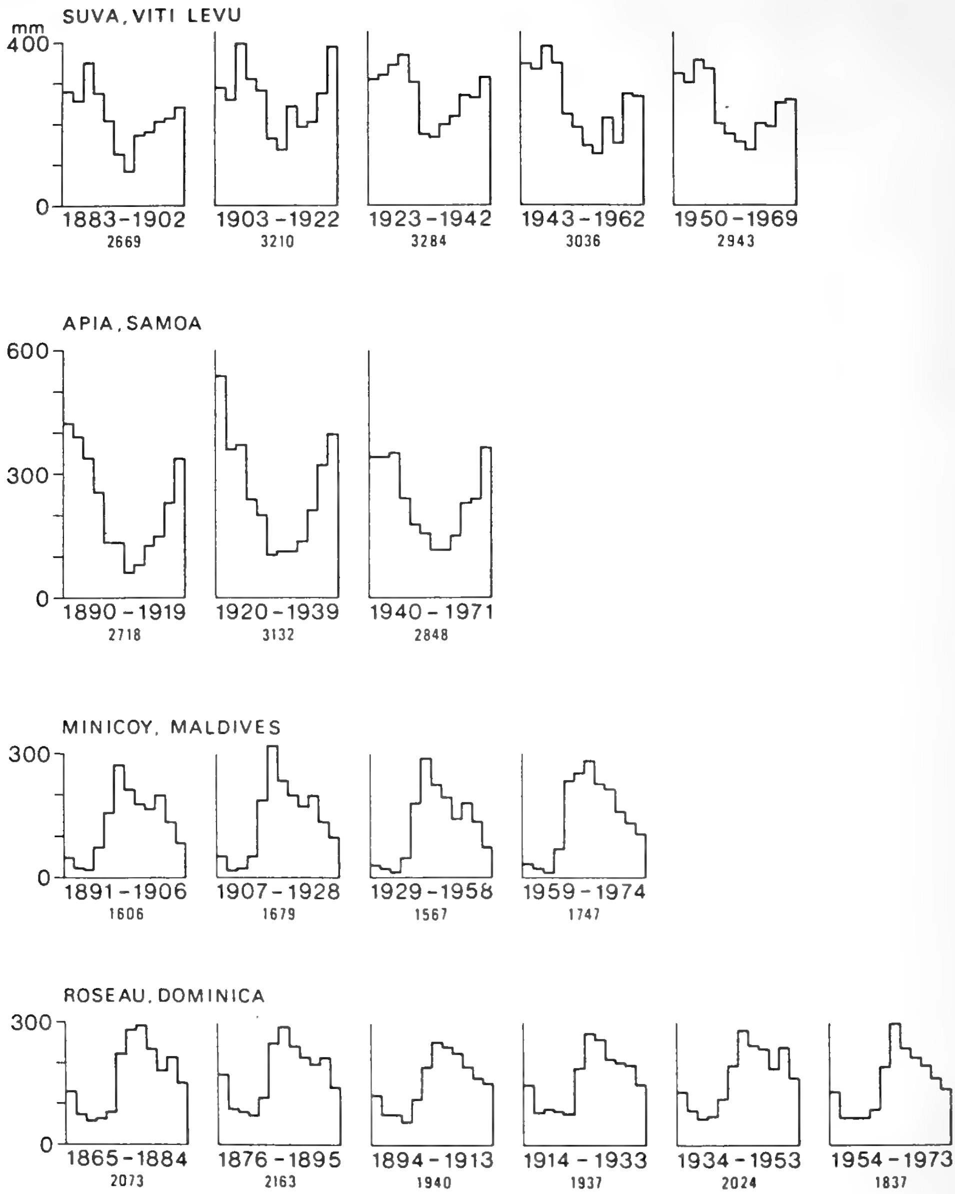


Figure 16. Changing seasonal distribution of monthly rainfall in different rainfall epochs at Suva, Viti Levu; Apia, Samoa; Minicoy, Maldives; and Roseau, Dominica. Figures beneath the histograms give annual means for each epoch.

Table 7. Frequency of high-intensity daily rainfalls in different rainfall epochs

Station	Period	Mean annual rainfall inches (mm)	Mean number of days > 1"/day	> 3"/day
St. Thomas BARBADOS	1889-1906	85.28 (2166)	22.0	2.3
	1907-1925	61.98 (1574)	11.7	0.6
	1926-1958	69.93 (1776)	14.5	1.1
	1962-1972	61.82 (1570)	11.6	0.7
Roseau DOMINICA	1921-1928	68.87 (1749)	11.7	0.8
	1929-1958	80.26 (2039)	18.9	1.7
	1959-1973	70.14 (1782)	17.2	1.1

great importance, however. The ecological and geomorphological effects of a high annual total made up of many small-magnitude rainfalls will be very different from those of a total composed of a small number of high-intensity falls. Cases where the transition from low to high annual rainfall epochs result from increases in the frequency of high-intensity rainfalls have been identified in the West Indies, and are documented in Table 7. Changed erosion rates, mass movements on slopes, increased sediment yields in rivers, sedimentation in nearshore areas, soil erosion exacerbated by deforestation, and lowered salinities in nearshore areas will all be accentuated under these conditions.

There are few analyses of rainfall intensity on atolls, though abundant data are available for study. Blumenstock and Rex (1960) showed from data collected at Enewetak Atoll, Marshall Islands, that the frequency distribution of daily rainfalls is highly skewed. Over the 13-month period August 1957-August 1958 the total rainfall at Enewetak Island in the southeast sector of the atoll was 1686 mm. Of this 871 mm, or 51.7%, fell on only 17 days, or 4.3% of the total number of days of record. The three highest daily falls were 77, 112 and 134 mm (3.04, 4.43 and 5.28 inches). Daily totals have also been studied at Aldabra Atoll, Indian Ocean (Hnatiuk 1979; Stoddart and Mole 1977; unpublished data), for the period 1968-1983, a total of 5845 days. During this period annual rainfall averaged 1103.3 mm, with extremes of 547.1 and 1467.4 mm. 22.3% of the total rainfall in this period fell on 0.79% of the total days, on days with rainfalls exceeding 50 mm (1.97 inches). Twelve days exceeded 100 mm per day (3.94 inches), and three exceeded 150 mm (5.91 inches). The three highest 24-hour rainfalls in this period were 159.3, 164.5 and 238.8 mm (6.27, 6.48 and 9.40 inches), the last on 19 April 1974. Further details are given

Table 8. Frequency of daily rainfalls at Aldabra Atoll, 1968-1983

Daily rainfall, mm	Number of days	Percent total number of raindays
0.1 - 5	1595	68.9
6 - 10	282	12.2
11 - 15	130	5.6
16 - 20	69	3.0
21 - 25	58	2.5
26 - 30	39	1.7
31- 35	44	1.9
36 - 40	18	0.8
41 - 45	19	0.8
46 - 50	9	0.4
51 - 55	11	0.5
56 - 60	6	0.3
61 - 65	3	0.1
66 - 70	6	0.3
71 - 75	3	0.1
76 - 80	2	0.1
81 - 85	3	0.1
86 - 90	2	0.1
91 - 95	1	0.04
96 - 100	1	0.04
101 - 200	13	0.6
200	1	0.04

in Table 8. There is a rather loose correlation between high annual rainfalls and the frequency of high-rainfall days. An earlier study (Stoddart and Mole 1977), over the shorter period 1968-1972, showed a better correlation between high annual rainfalls and the number of days with falls of 10-25 mm per day. This study also showed that 70% of all rain-days had less than 5 mm/day and 90% less than 15 mm/day (Stoddart and Mole 1977, 3, Table 12).

Magnitude and frequency of droughts

Mention has already been made of drought conditions in the southern Gilberts associated with the equatorial Pacific upwelling pattern (Table 6). Duration is a parameter as significant as absolute lack of rainfall in island droughts: Table 9 describes some atoll droughts characterised by both very low or even zero rainfalls and long duration. Three of the islands in Table 9 are located in the Pacific equatorial zone already described. In ecological terms drought can be defined by monthly rainfalls falling below a given threshold. Sequences of dry months, defined as months with less than 100 mm (3.94 inches) of rainfall, have been investigated: Table 10 and Figure 17 give data on

Table 9. Notable atoll droughts

Aranuka, Gilbert Islands:

29 months, August 1966–December 1968: total 146 mm (including zero rainfall February–June 1968 and August–October 1968).

Christmas Island (Pacific):

19 months, June 1949–January 1951: total 193 mm

Inlcuding 8 months, June 1949–February 1950, with a total of 22 mm

Malden Island:

14 months, January 1891–February 1892, total 220 mm

14 months, January 1895–February 1896, total 140 mm

9 months, June 1901–February 1902, total 45 mm

Alphonse Island, Amirantes:

7 months, June 1959–December 1959, total 7.6 mm

Aldabra Atoll:

6 months, June–November 1949, total 41 mm (three consecutive months with zero rainfall)

drought length so defined for several locations (Suva, Minicoy, Dominica, Apia, and Mahe) for each of the rainfall epochs previously identified. Longer drought sequences are more frequent in dry than in wet epochs, and very long droughts may occur in very dry periods. Gross fluctuations in drought frequency can also be identified over time using twenty-year moving averages, and Figure 17 also gives the twenty-year moving averages of numbers of dry months (with less than 100 mm rainfall per month) for the islands named. It is interesting to note that the frequency of extended periods of drought varies quite markedly at Minikoi even when the mean number of months of drought remains relatively invariant.

Drought duration has also been studied on a daily basis, using definitions both of no rainfall at all and of a threshold rainfall of 5 mm per day, for the five years 1968-1972 at Aldabra Atoll. The data in Figure 18 show an important asymmetry, in that wet periods are generally much shorter than dry periods, and some dry periods can be very long indeed.

An alternative approach to drought, utilising evapotranspiration measurements, has been explored in the context of agricultural potential for central Pacific islands by Nullet (1987), Nullet and Gianbucella (1988) and Gianbucella et al. (1988).

Table 10. 20 yr frequencies of length of droughts (months with less than 100 mm rainfall) in different rainfall epochs

Station	Period	Duration, months							
		1	2	3	4	5	6	7	8
Suva									
VITI LEVU	1883-1905	16.0	10.0	2.0	2.0				
	1906-1941	17.2	2.8	1.7					
	1942-1969	21.4	3.6	2.1	2.9				
Roseau									
DOMINICA	1865-1898	17.1	6.5	5.9	4.1	0.6	0.6		
	1899-1928	18.0	7.3	4.0	5.3	2.7	0.7		
	1929-1958	11.3	6.7	6.0	2.7	2.0	2.0		
	1959-1989	17.8	2.2	5.2	4.4	2.2	2.2	1.5	0.7
Minicoy									
MALDIVE IS.	1891-1906	13.8	2.5	5.0	3.8	10.0	2.5		
	1907-1928	15.5	1.8	4.6	3.6	6.4	2.7	1.8	0.9
	1929-1958	16.7	4.0	3.4	4.7	8.0	2.7	1.3	
	1959-1974	8.8	2.5	2.5	5.0	3.8	5.0	2.5	1.3
Apia									
SAMOA	1890-1919	10	7.3	3.3	2	2.6	0.6		
	1920-1939	17	6	1	3	0	1		
	1940-1971	18.1	5.6	3.8	1.3				
Mahe									
SEYCHELLES	1891-1904	17.1	4.3	7.1	4.3	1.4	1.4		
	1905-1922	15.6	8.9	10.0	1.1	1.1	1.1		
	1923-1937	22.7	9.3	4.0	1.3	1.3			
	1938-1954	18.8	3.5	3.5	5.9	3.5	2.4		
	1955-1968	17.1	5.7	7.1	2.9	1.4			
	1969-1989	12.4	7.6	1.9	4.8	3.8	1.9	1.0	

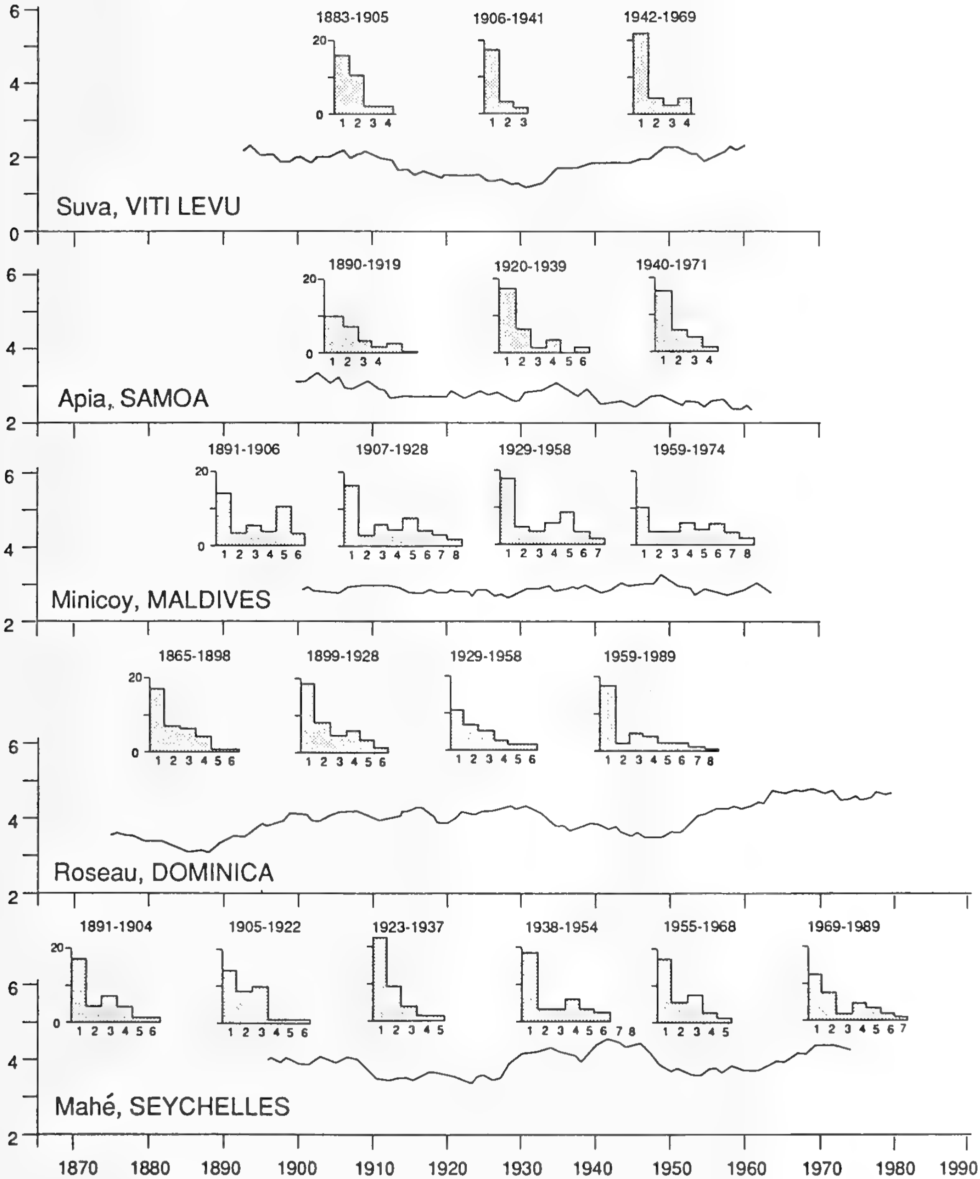


Figure 17. Twenty-year running means of numbers of dry months and frequency distribution (per 20 years) of lengths of dry periods for different time periods at Suva, Viti Levu; Apia, Samoa; Minicoy, Maldives; Roseau, Dominica; and Mahe, Seychelles.

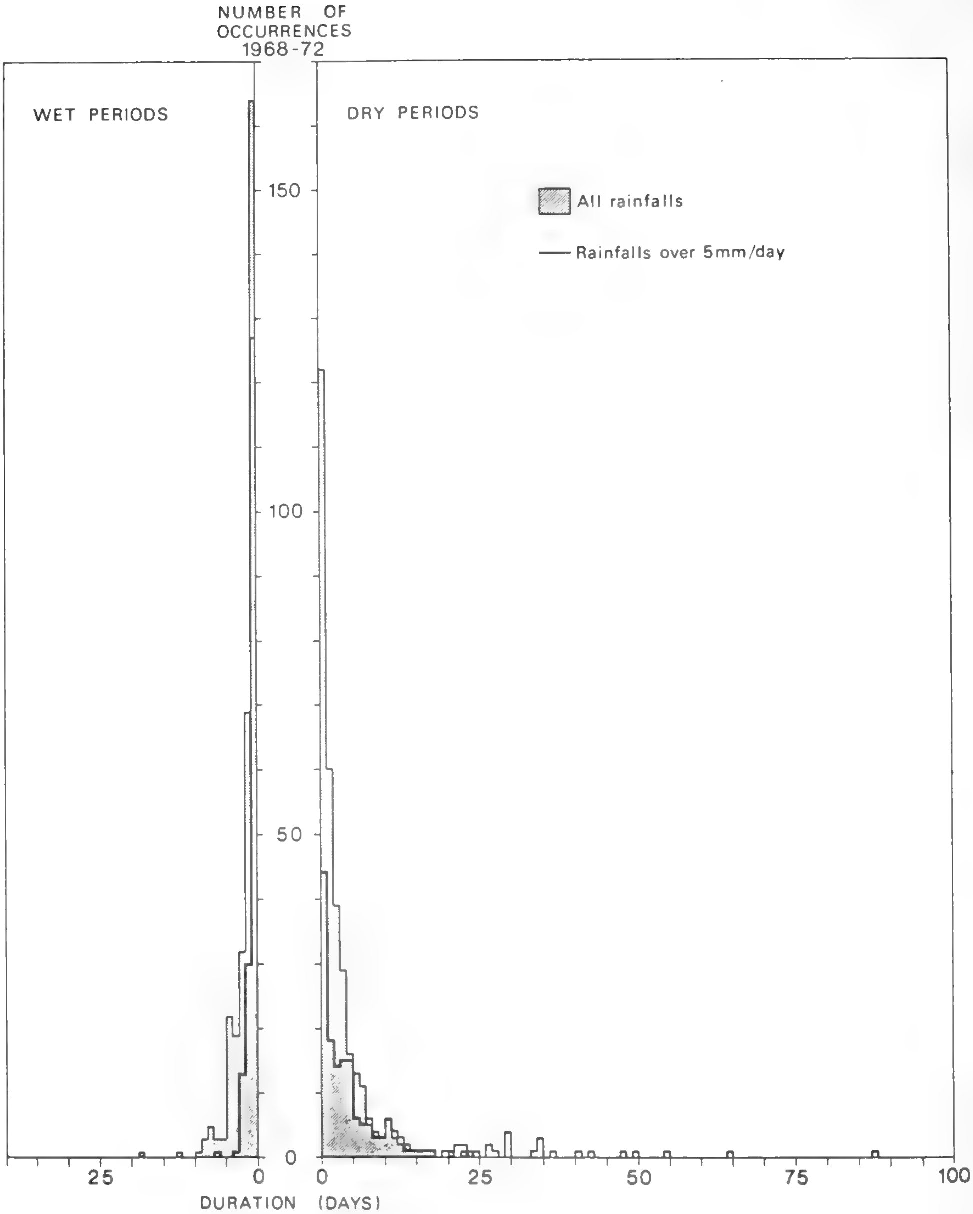


Figure 18. Frequency and duration of wet and dry spells at Aldabra Atoll, western Indian Ocean, 1968-1972 (From Stoddart and Mole 1977).

HURRICANES

Tropical hurricanes, defined as low pressure systems with wind speeds in excess of 120 km/h, are probably the single most important catastrophic event regularly experienced in the reef seas. Individual storm systems, moving at 15-25 km/h, have a mean area of 250,000 km^2 and diameter of 500-600 km; winds circulate round them in an anticlockwise direction in the northern hemisphere and clockwise in the southern. Figure 19 shows the general distribution of the hurricane belts, though it is clear from geomorphological evidence that hurricanes have occurred in the recent past in areas where there is no historical record of them.

Hurricanes act in a variety of ways (Stoddart 1971b, Dupon 1987). Wind speeds which may exceed 275 km/h (150 kts) can cause massive damage to forests and to economic crops such as coconuts and bananas, and also damage to houses, other installations such as fish traps and pearl farms, and equipment such as boats. Wind-generated storm surges can raise the local level of the sea 5 m or more above its tidally-predicted position and cause overtopping of islands and widespread inundation, especially in areas adjacent to coastal shelves. Thus Sally caused a 5 meter storm surge on Rarotonga in January 1987. These effects are particularly serious in microtidal reef areas where island altitudes are low. Wind-driven waves can lead to severe reef destruction, mobilisation of coarse sediment and its deposition on reef flats, and erosion of existing shorelines and land surfaces (waves 23.6 m high were measured during Hurricane Camille in the Gulf of Mexico in 1969: Earle 1975): reef blocks 4-6 meters in greatest dimension were deposited on reef fleets, on Raroia Atoll in 1903 and Rangiroa in 1906. Rainfall, especially in near-stationary storms, can reach extraordinary levels. There is a large literature on the economic (Weaver 1968) and social (Lessa 1964, Yamashita 1965, Barker and Miller 1990) consequences of such storms on small islands, where they may often serve as catalysts in accelerating change. There is, too, a large literature on their geomorphological and ecological effects, both terrestrial and marine (Stoddart 1971b).

Earlier studies, such as those of the effects of Ophelia at Jaluit Atoll, Marshall Islands, in 1958 (Blumenstock et al. 1961) and Hattie on the Belize reefs and cays in 1961 (Stoddart 1963) stressed the destructive effects on island morphology and vegetation of such intense storms, though it was clear from these studies that such effects varied both spatially in any particular storm and also with storm intensity. Bebe at Funafuti Atoll, Tuvalu, in 1972 demonstrated how storms impacting linear atoll islands (motus) may lead to land accretion rather than shoreline erosion. This storm had maximum winds in excess of 180 km/h and a surge up to 4 m above mean high water level. It formed a rubble ridge on the southeastern seaward reef flat 18-19 km long, 30-40 m wide and 3.5 m high; the volume of this ridge was estimated at 1.4×10^6 m^3 and its mass as 2.8×10^6 metric tonnes; the largest boulder included in it had a diameter of 7 m (Maragos et al. 1973; Baines et al. 1974).

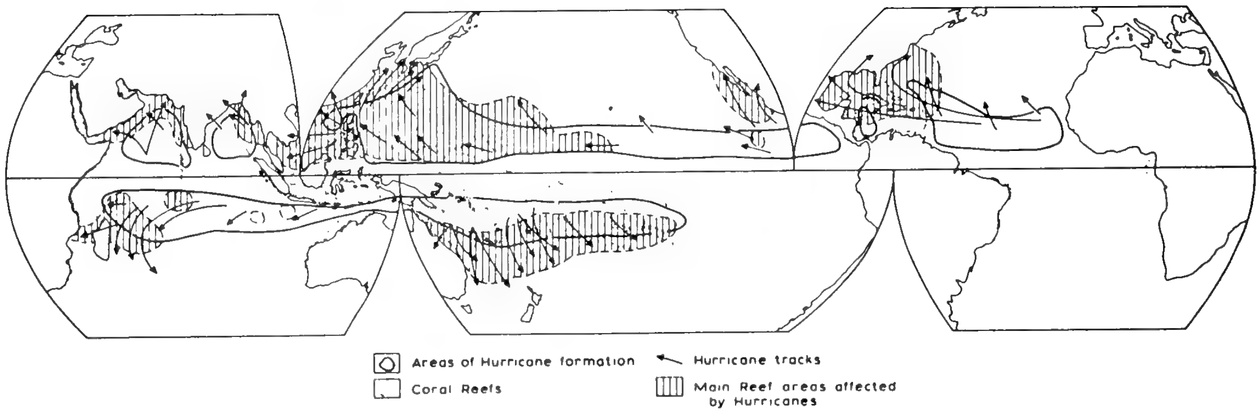


Figure 19. Distribution of main hurricane areas (From Stoddart 1971b).

Over succeeding years the ridge migrated shoreward until it became attached to the seaward beach of the motu (Baines and McLean 1976). A comparable storm on Ontong Java Atoll, Solomon Islands, in 1967 created a similar reef-flat rubble ridge 35 km long, 20 m wide, with a crest 1-3 m above mean sea-level, and this too migrated shoreward to become attached to motu shorelines over the next 19 years (Bayliss-Smith 1988). Bayliss-Smith concluded from the latter case that storms of such magnitude may be destructive on small islands (cays), but act as a source of sediment supply and episodic accretion on larger islands (motus), and also suggested that these effects varied systematically with comparable storms over the length of the Holocene (Bayliss-Smith 1988, 388-390). Woodley and co-workers (1981), however, also demonstrated the spatial variability of the effects of individual storms in terms of depth and aspect in the case of Hurricane Allen on the Jamaican reefs in 1980. This was one of the most intense storms of the century, with maximum wind speeds of 285 km/h and observed waves 12 m high in water only 15 m deep.

Extreme storms appear to have been more frequent in recent years, witness David and Gilbert in the Caribbean and Gulf of Mexico in 1979 and 1988 (Gilbert had the lowest pressure ever recorded in the western hemisphere [888 mb] and wind speeds up to 220 km/h) and Hugo in the Lesser Antilles in 1989. The six storms that occurred in the Tuamotu-Society Islands area between December 1982 and April 1983 (especially Orama), are particularly noteworthy in this respect (Figure 20). No observations on subaerial effects of these Pacific storms have been published, but reef damage was severe (Laboute 1985; Harmelin-Vivien and Laboute 1986). The frequency of central Polynesian storms appears directly linked to El Niño events, especially through increased sea-surface temperatures, and Emanuel (1987) has suggested that predicted global warming will lead to an increase in frequency and strength of major storms and an extension of the hurricane belts as sea-surface temperatures increase over future decades.

It is clear from the historical record that hurricane frequencies vary over time, even though analysis is made difficult by the paucity of accurate records in earlier years, especially in more remote locations. Milton (1974) has analysed changing frequencies in the Indian Ocean and Australian regions (Figure 21): his data show high frequencies between 1911 and 1921, low frequencies between 1921 and about 1945, and higher frequencies after that date. In the western Indian Ocean low storm frequencies in the period 1900-1929 were associated with lower sea-surface temperatures, and higher frequencies in the period 1930-1959 with higher temperatures. This temporal variability was also associated with spatial shifts: the locus of maximum activity, which was concentrated in the northern Madagascar area in the 1930s, shifted northwards in the decade 1941-1950 and southwards during 1951-1960 (Stoddart and Walsh 1979). On the Great Barrier Reef, over the period 1910-1969, storm frequencies were highest ca 1950 and lowest in the decade 1920-1930, with pronounced differences in latitudinal distribution (Coleman 1971; Stoddart 1978).

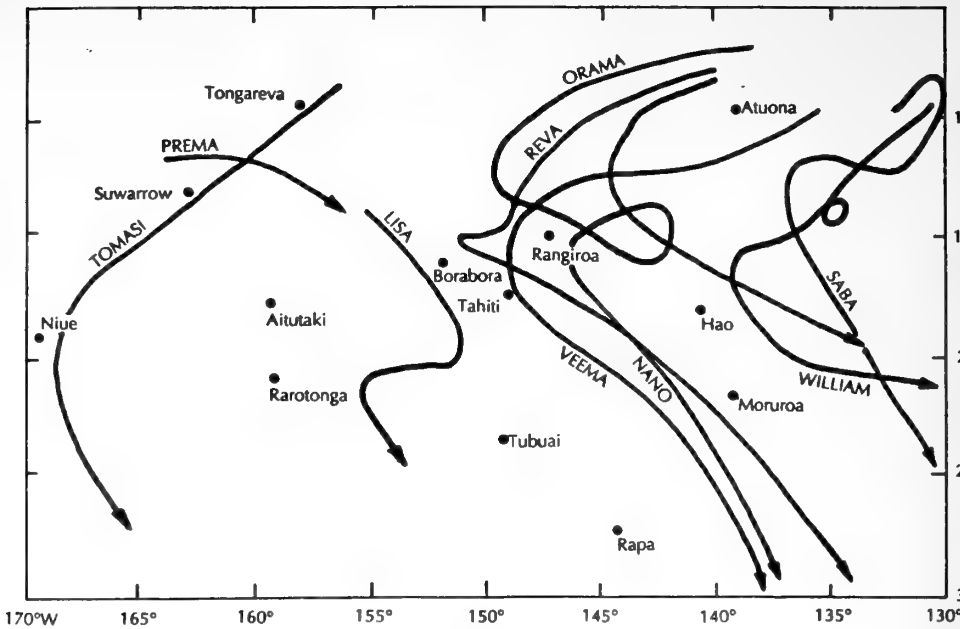


Figure 20. Hurricane tracks in the Tuamotu-Society Islands area during the period December 1982 through April 1983.

Likewise there have been marked changes in both regional frequency and intraregional spatial pattern of tropical cyclones in the North Atlantic/Caribbean, where reasonably comprehensive charted records extend back to 1871 (Neumann et al. 1978). Frequencies of tropical cyclones of at least storm intensity were high in the late nineteenth century, low in the 1910s and 1920s, very high from the 1930s to 1950. Though at the regional scale cyclone frequency has remained high in the 1960s, 1970s and 1980s, there has been a significant eastward shift in tracks into the Atlantic and frequencies over most of the Caribbean have fallen sharply (Eyre & Gray 1990, Walsh & Reading 1991). Furthermore, the frequency of cyclones of hurricane intensity has fallen in recent decades from 6.3 per annum in the 1950s to 3.5 and 4.0 per annum in the 1970s and 1980s respectively, with no indication yet of an increase with global warming.

Changes in tropical cyclone frequency over much longer timescales have been investigated for parts of the Caribbean using historical records (Walsh 1977, Walsh & Reading 1991) The particularly comprehensive records for the Lesser Antilles (Figure 22) indicate roughly equal peaks in cyclone activity in the periods 1765-92, 1804-37, 1876-1901 and 1928-58; very low frequencies from 1650-1764 at the height of the Little Ice Age, in 1793-1803 and

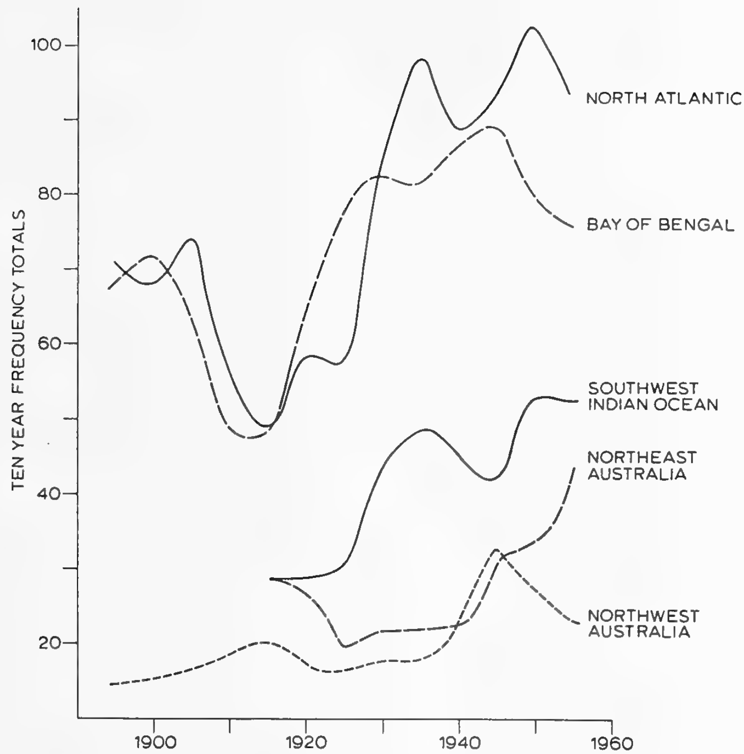


Figure 21. Ten-year frequency totals of hurricanes in different areas (From Milton 1974).

in 1835-75; and moderately low frequencies in 1902-27 and 1959-89. Even longer records for Hispaniola show a very similar temporal pattern and suggest very low frequencies during the whole of the sixteenth and seventeenth centuries. These sub-regional fluctuations can be used to reconstruct time series at a regional scale (Figure 23). Patterns of change at an individual island group level (Table 11) in the Lesser Antilles differ, reflecting latitudinal shifts in predominant tracks from epoch to epoch. Peak frequency in the Leewards/Virgins and in the French Islands and Dominica occurred in 1765-1793, but in 1876-1901 in the more southerly Windwards and in Trinidad and Tobago. For the charted period since 1871, the mean latitude at which cyclones passed westward through 61°W (which approximates to the north-south axis of the Islands) has been calculated. The mean track latitude was

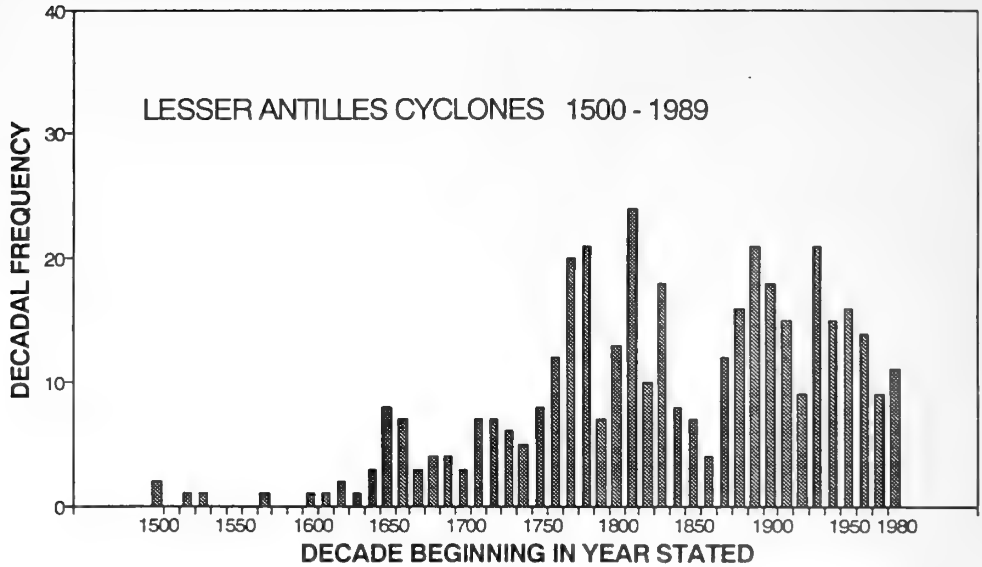


Figure 22. Ten-year frequency of cyclones in the Lesser Antilles, 1500-1989. Records are considered reasonably comprehensive since 1650. (From Walsh and Reading 1991)

21.0°N in 1871-75, more southerly at 18.4°N in 1876-1901, somewhat more northerly in both the 1902-27 (19.0°N) and 1928-58 (18.9°N) periods, but much further south at 17.7°N since 1959 .

Walsh & Reading (1991) found that the Atlantic/Caribbean appear to be more linked to shifts in key aspects of the atmospheric circulation rather than to changes in sea surface temperature or the frequency of El Niño events (as indicted by the chronology since 1500 of Quinn et al. 1987). Although strong El Niño events during the current century have been shown to be associated with a reduced frequency and changed spatial distribution of cyclones of hurricane intensity in the North Atlantic (Eyre & Gray 1990, Gray & Sheaffer 1991), it does not appear to have been the main influence on cyclones in the longer term.

IMPLICATIONS

The variations in climatic elements, notably rainfall, viewed as inputs to the terrestrial ecosystem, which we have identified, together with other perturbations, are on such a scale that they must have serious implications both for the structure of island ecosystems and for the processes at work within them.

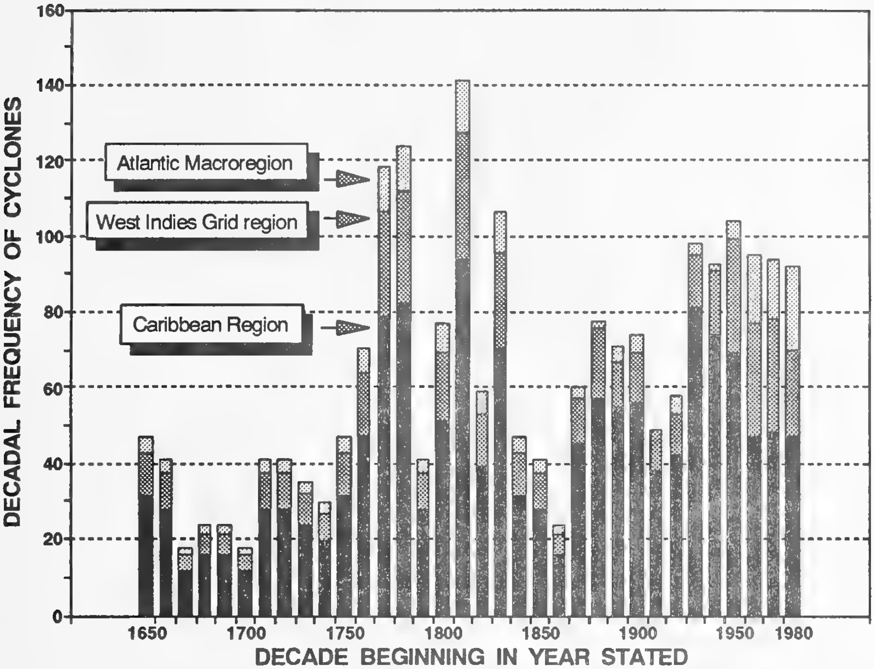


Figure 23. Reconstructed ten-year frequency of cyclones in the Atlantic, Caribbean and West Indian regions, 1650-1989. (From Walsh and Reading 1991).

Rainfall magnitudes, together with seasonality, form a basic input in the geomorphic system. Fournier (1960) has demonstrated a fairly simple relationship between suspended sediment yield in drainage basins and a parameter p^2/P, where p is the precipitation in mm of the month with highest rainfall, and P is the mean annual rainfall in mm. Fournier showed the relationship between 8 and 80 for values of p^2/P and from less than 100 to over 1500 tonnes/km^2/year for suspended sediment yield (cf. Stoddart 1969, 183). Table 12 shows how p^2/P varies between each of the identified rainfall epochs at Viti Levu and Samoa in the Pacific, Minicoy and Mahe in the Indian Ocean, and Dominica in the West Indies. The limits of variation at these stations are respectively 41.8-51.5 at Suva, 48.3-95.5 at Apia, 34.9-59.8 at Minicoy, 50.4-81.3 at Mahe, and 34.7-49.2 at Dominica. At Apia p^2/P during 1920-1939 was almost exactly twice that for 1940-1971. These figures vividly illustrate the fact that it is not possible to predict, for example, the erosional consequences of deforestation on tropical islands without understanding the rapid and large-scale fluctuations in intensity of erosional processes.

Table 11. Changes in mean annual frequency of tropical cyclones within the Lesser Antilles 1650-1989

Period	Leewards/ Virgin Is.	French Is. & Dominica	Windward Islands	Trinidad & Tobago	Lesser Antilles
1650-1764	0.28	0.22	0.17	0.01	0.56
1765-1793	1.07	0.96	0.29	0.14	1.96
1794-1805	0.27	0.00	0.00	0.09	0.36
1806-1837	0.94	0.94	0.62	0.09	1.79
1838-1875	0.42	0.21	0.24	0.03	0.66
1876-1901	0.88	0.69	0.81	0.15	1.96
1902-1927	0.54	0.62	0.62	0.00	1.27
1928-1958	0.71	0.55	0.61	0.13	1.74
1959-1989	0.42	0.45	0.42	0.10	1.13

Such variations in climate also have substantial ecological implications. We have already noted the correspondence between rainfall and vegetation in the Marshall Islands (Figure 8), as systematised in the 'Fosberg zones', originally described for the northern Marshalls and subsequently extended from Wake Island in the north southwards to Tuvalu (Fosberg 1956; Wiens 1962; Catala 1957; Amerson 1969). In Fosberg's zone 1 (Wake and Taongi) no coconuts grow. In zone 2 at Bikar there is *Pisonia* forest. In zone 3 there is *Cordia, Pemphis,* mixed forest and coconuts. In zone 4 there is *Neisosperma* forest and breadfruit; in zone 5 coconuts and breadfruit; and in zone 6 dense forest. Zones 7, 8 and 9 mirror zones 5, 4 and 3 on the south. If, as in Figure 7, these zones are defined simply in terms of mean annual rainfall, then fluctuations over time in the mean of ±25 per cent are sufficient to move an atoll from the centre of one zone to the centre of another; smaller fluctuations can take an atoll across a zonal boundary. We have seen that fluctuations of up to or exceeding 25 per cent have occurred at some tropical stations between successive rainfall epochs, and changes of 10 per cent are common.

This observation raises important questions about the environmental controls of such vegetation units, and about the rates at which vegetation (especially shrubs and trees) can respond to changes in environmental conditions. It may, for example, be hypothesized that such responses are asymmetric, with herbaceous vegetation responding more rapidly to increasing wetness than to drought, and shrubs and trees being more responsive to drought than increasing wetness. Further studies are needed of the relationships between such parameters as rainfall periodicity and

Table 12. Variation in p^2/P in different rainfall epochs for tropical island stations

Period	Mean Ann. Rainfall mm	Highest Mon. Mean mm	p^2/P
SUVA, FIJI			
1883-1902	2682	361 (Mar)	48.7
1903-1922	3210	406 (Mar)	51.5
1923-1942	3284	371 (Apr)	41.8
1943-1962	3036	390 (Mar)	50.2
1950-1969	2943	360 (Mar)	44.1
APIA, SAMOA			
1891-1919	2718	427 (Jan)	67.1
1920-1939	3132	547 (Jan)	95.5
1940-1971	2870	371 (Dec)	48.3
ROSEAU, DOMINICA			
1865-1884	2073	298 (Aug)	43.0
1876-1895	2163	296 (July)	40.6
1894-1913	1940	259 (July)	34.7
1914-1933	1937	274 (July)	38.8
1934-1953	2024	284 (July)	39.9
1954-1973	1837	300 (July)	49.2
MINICOY, MALDIVE ISLANDS			
1891-1906	1606	274 (June)	46.7
1907-1928	1679	317 (June)	59.8
1929-1958	1567	292 (June)	54.4
1959-1974	1747	283 (June)	34.9
MAHE, SEYCHELLES			
1891-1904	2600	460 (Jan)	81.3
1905-1922	2192	388 (Jan)	68.7
1923-1937	2652	390 (Jan)	57.3
1938-1954	2038	320 (Jan)	50.4
1955-1968	2585	451 (Jan)	78.6
1969-1989	2082	358 (Jan)	61.7

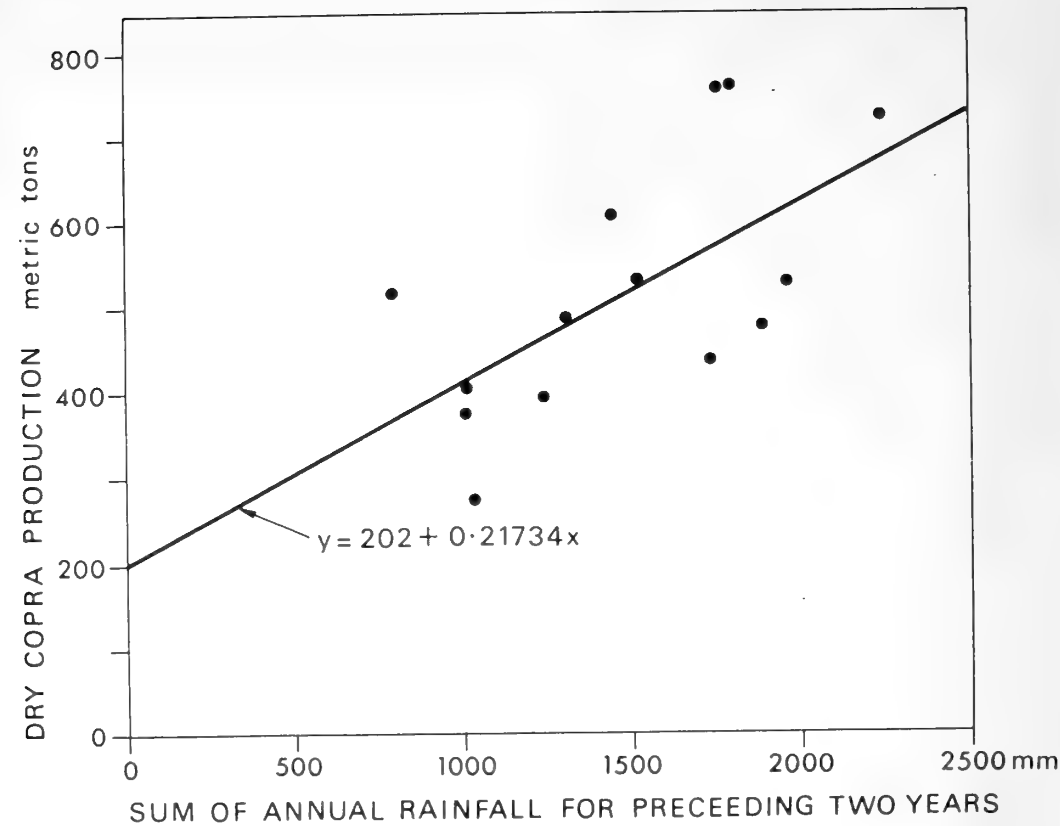


Figure 24. Relationship between rainfall and copra production at Kiritimati [Christmas Island], Line Islands (From Jenkin and Foale 1968).

hurricane magnitude and frequency and the life-cycles of island plants. And as demonstrated by the response of the Christmas Island seabird populations to the 1982-1983 El Niño event, perturbations in climate and vegetation are transmitted through other components of the island ecosystem.

The data also suggest substantial constraints on agricultural activities. Jenkin and Foale (1968) have shown a relationship between copra production and the aggregate rainfall of the two previous years at Kiritimati (Line Islands) (Figure 24), and in Trinidad Smith (1966) has shown that there is an even closer relationship between copra yield and the rainfall of the dry season of the two previous years (Figure 25). Such relationships have been observed at many tropical stations (e.g. Patel and Anandan 1936), not only for copra but also for sugar (Smith 1962; Chang et al. 1963; Oguntoyinbo 1966). There is

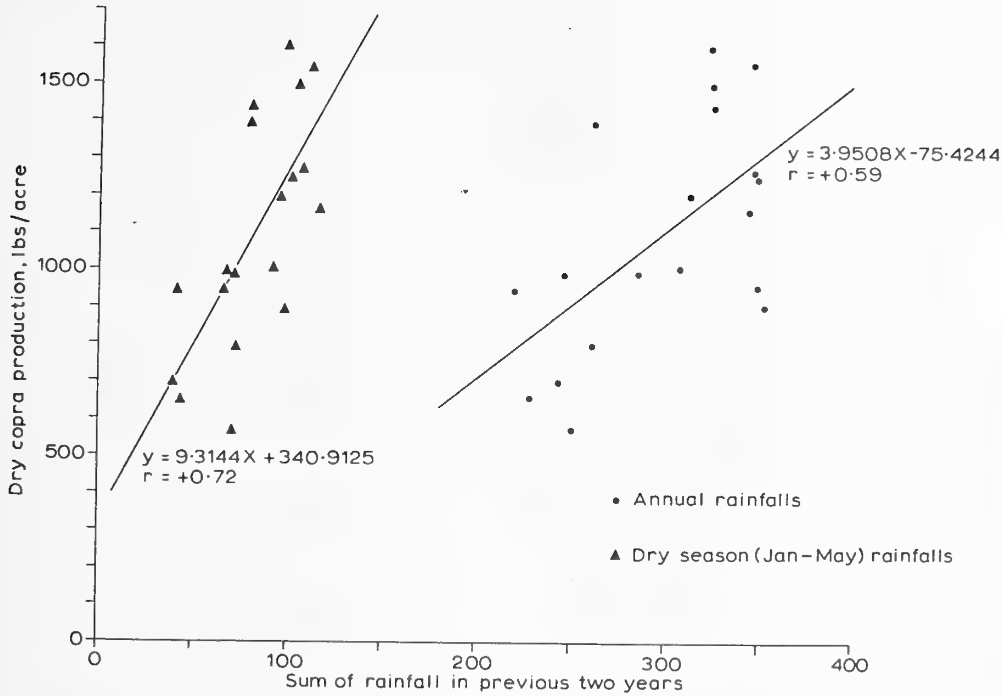


Figure 25. Relationship between annual and dry season rainfall and copra production, Perseverance Estate, Trinidad, 1941-1959 (Data from Smith 1966).

little doubt that, as Marshall (1956) suggested, variations in rainfall on the scale now identified must have had profound consequences for human activities and especially for agriculture.

Finally, it is worth noting that the effects of these climatic variations must extend throughout the terrestrial ecosystems of islands. Just as the Fosberg zones demonstrate a close linkage between mean annual rainfall and vegetation, so Amerson (1969) has shown an equally close linkage between rainfall and bird species diversity (Figure 26). At Aldabra Atoll D . W. Frith (1979) has demonstrated how rainfall seasonality controls insect abundance, and C. B. Frith (1976) has shown how insect numbers affect breeding performance in predominantly insectivorous landbirds. Likewise at the same location, Coe et al . (1979) have used an equation developed by Rosenzweig (1968) to calculate net primary production under different rainfall conditions. They have shown how food consumption by the Giant Tortoise *Geochelone gigantea* varies seasonally from 380±64.8 g dry mass/day to only 110±77.9 g in the late dry season. On a longer time scale they suggest that secondary

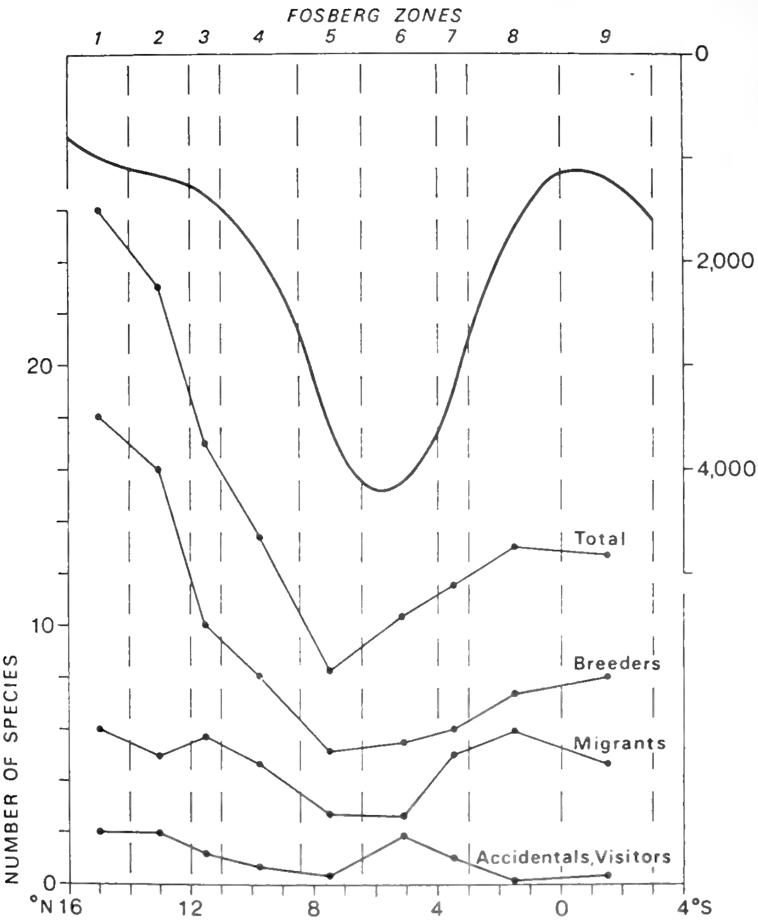


Figure 26. Relationship between mean annual rainfall, latitude, and numbers of birds species for the Marshall and Gilbert Islands (Data from Amerson 1969).

production is itself controlled by primary production, ranging for tortoises from 624 kg/km^2/year in a dry year (547 mm annual rainfall) to 3245 kg/km^2/year in a wet year (1487 mm); production is itself a key to biomass. Climate and its variability is thus seen as a fundamental control of the functioning of the terrestrial ecosystem of Aldabra Atoll. We may go further and speculate that substantial variations in rainfall, as well as catastrophic damage by hurricanes, may over quite short periods of time, measured in decades, have implications for changes in species diversity and even for the extinction or survival of individual taxa on islands.

CONCLUSION

We have therefore shown that island environments are highly variable in a number of critical ways, on time scales ranging from the last few thousand years to very short period fluctuations. We suggest that analyses of human adaptability on tropical islands should begin with a presumption of temporal variability in critical environmental inputs, rather than with a reliance on long-term mean conditions. We have suggested that such changes may have important implications for the economic viability of island populations, through effects on crop yields, and we have shown that in some cases, at least, such as the Phoenix Islands, environmental variations in recent years have exceeded even the thresholds of survival for indigenous human communities. In these responses human populations mirror those of other components, both plant and animal, of the terrestrial island ecosystem.

ACKNOWLEDGEMENT

Stoddart has great pleasure in thanking F. R. Fosberg for his great assistance and encouragement in everything to do with islands, both for himself and for his students, since 1959. Part of this paper results from two expeditions with Dr. Fosberg, one with Roger Clapp, to the Phoenix Islands in 1973 and 1975, with the support of the Department of Defense, the Smithsonian Institution and the Royal Society. Walsh's work in the West Indies has been supported by the Natural Environment Research Council during 1972-1975, and the Smuts Memorial and Philip Lake Funds of Cambridge University. He thanks the Caribbean Meteorological Institute, Barbados, and the Department of Agriculture, Dominica, for their aid. We would like to thank M. J. Fox and Mr. R. Lajoie of the Directorate of Civil Aviation, Seychelles, and Mr. Frank Farnum of the Caribbean Meteorological Institute, Barbados, for providing some of the meteorological data. Mr. M. Young and Mr. Guy Lewis drew the figures. Evan C. Evans made detailed comments on an earlier version of this paper.

REFERENCES

Amerson, A. B., Jr. 1969. Ornithology of the Marshall and Gilbert Islands. *Atoll Research Bulletin,* 127, i-viii, 1-348.

Anderson, T. and Flett, S. S. 1902. Report on the eruptions of the Soufrière in St Vincent in 1902, and on a visit to Montagne Pelée in Martinique. Part I. *Philosophical Transactions of the Royal Society of London*, A 200, 353-548.

Anderson, T. 1908. Report on the eruptions of the Soufrière in St Vincent in 1902, and on a visit to Montagne Pelée in Martinique. Part II. The changes in the districts and the subsequent history of the volcanoes. *Philosophical Transactions of the Royal Society of London,* A 208, 275-331.

Andrews, J. T. 1973. The Wisconsin Laurentide ice sheet: dispersal centers, problems of rates of retreat, and climatic implications. *Arctic and Alpine Research,* 5, 185-199.

Baines, G. B. K., Beveridge, P. K. and Maragos, J. E. 1974. Storms and island building at Funafuti Atoll, Ellice Islands. *Proceedings of the 2nd International Coral Reef Symposium* 2, 485-496.

Baines, G. B. K. and McLean, R. F. 1976. Sequential studies of hurricane deposit evolution at Funafuti Atoll. *Marine Geology,* 21, M1-M8.

Baird, D. E. 1965. The effects of the eruption of 1961 on the fauna of Tristan da Cunha. *Philosophical Transactions of the Royal Society of London,* B 249, 425-434.

Barber, R. T. and Chavez, F. P. 1983. Biological consequences of El Niño. *Science,* 222, 1203-1210.

Barber, R. T. and Chavez, F. P. 1986. Ocean variability in relation to living resources during the 1982-83 El Niño. *Nature,* 319, 279-285.

Barker, D. and Miller, D. 1990. Hurricane Gilbert: anthropomorphizing a natural disaster. *Area*, 22, 107-116.

Barnett, T. P. 1984. The estimation of global sea-level change: a problem of uniqueness. *Journal of Geophysical Research*, 89, 7980-7988.

Bayliss-Smith, T. P. 1988. The role of hurricanes in the development of reef islands, Ontong Java Atoll, Solomon Islands. *Geographical Journal*, 154, 377-391.

Bjerknes, J. 1969. Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, 97, 163-172.

Bloom, A. L., Broecker, W. S., Chappell, J., Matthews, R. K. and Mesolella, K. J. 1974. Quaternary sea-level fluctuations on a tectonic coast: new $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea. *Quaternary Research*, 4, 185-205.

Blumenstock, D. I. and Rex, D. F. 1960. Microclimatic observations at Eniwetok. *Atoll Research Bulletin*, 71, i-ix, 1-158.

Bourrouilh-Le Jan, F. G. and Talandier, J. 1985. Sédimentation et fracturation de haute energie en milieu récifal: tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la géomorphologie d'un atoll: motu et hoa, à Rangiroa, Tuamotu, Pacifique SE. *Marine Geology*, 67, 263-333.

Braithwaite, C. J. R., Taylor, J. D. and Kennedy, W. J. 1973. The evolution of an atoll: the depositional and erosional history of Aldabra. *Philosophical Transactions of the Royal Society of London*, B 266, 307-340.

Brattstrom, B. H. 1963. Barcéna volcano, 1952: its effect on the fauna and flora of San Benedicto Island, Mexico. J.L. Gressitt, ed.: *Pacific basin biogeography* (Honolulu: Bishop Museum Press), 499-524.

Brookfield, H. C. and Hart, D. 1966. Rainfall in the tropical southwest Pacific. Canberra: Australian National University.

Brown, B. E., ed. 1990. Coral bleaching. *Coral Reefs*, 8, 153-232.

Bruun, P. 1962. Sea level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division American Society of Civil Engineers* 71, 1729-1754.

Bruun, P. 1983. Review of conditions for uses of the Bruun rule of erosion. *Coastal Engineering*, 7, 77-89.

Bruun, P. 1988. The Bruun rule of erosion by sea-level rise: a discussion on large-scale two- and three-dimensional usages. *Journal of Coastal Research*, 4, 627-648.

Buddemeier, R. W. and Holladay, G. L. 1977. Atoll hydrology: island groundwater characteristics and their relationship to diagenesis. *Proceedings of the 3rd International Coral Reef Symposium* 2, 167-174.

Cane, M. A. 1986. El Niño. *Annual Review of Earth and Planetary Sciences* 14, 43-70.

Catala, R. L. A. 1957. Report on the Gilbert Islands: some aspects of human ecology. *Atoll Research Bulletin*, 59, 1-187.

Caviedes, C. N. 1984. El Niño 1982-83. *Geographical Review*, 74, 267-290.

Chappell, J. 1982. Evidence for smoothly falling sea level relative to north Queensland, Australia, during the past 6000 years. *Nature*, 302, 406-408.

Chang, J., Campbell, J., and Robinson, F. E. 1963. On the relationship between water and sugarcane yield in Hawaii. *Agronomy Journal*, 55, 450-453.

Chappell, J. 1974. Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea-level changes. *Geological Society of America Bulletin*, 85, 553-570.

Chappell, J. and Veeh, H. H. 1978. Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island. *Geological Society of America Bulletin*, 89, 356-368.

Coe, M. J., Bourn, D. and Swingland, I. R. 1979. The biomass, production and carrying capacity of giant tortoises on Aldabra. *Philosophical Transactions of the Royal Society of London*, B 286, 163-176.

Cohen, T. J. and Sweetser, E. I. 1975. The 'spectra' of the solar cycle and of data for Atlantic tropical cyclones. *Nature*, 256, 295-296.

Coleman, F. 1971. *Frequencies, tracks and intensities of tropical cyclones in the Australian region, November 1909 to June 1969*. Canberra: Department of the Interior, Bureau of Meteorology. 42 pp.

Colgan, M. W. 1990. El Niño and the history of eastern Pacific reef building. P. W. Glynn, ed.: *Global ecological consequences of the 1982-83 El Niño-Southern Oscillation* (Amsterdam: Elsevier), 183-232.

Cook, C. B., Logan, A., Ward, J., Luckhurst, B., and Berg, C. J., Jr. 1990. Elevated temperatures and bleaching on a high latitude coral reef: the 1988 Bermuda event. *Coral Reefs*, 9, 45-49

Cox, D. C. and Mink, J. F. 1963. The tsunami of 22 May 1960 in the Hawaiian Islands. *Bulletin of the Seismological Society of America*, 53, 1191-1209.

Cubit, J. D. 1985. Possible effects of recent changes in sea level on the biota of a Caribbean reef flat and predicted effects of rising sea levels. *Proceedings of the 5th International Coral Reef Congress*, 3, 111-118.

Denham, D. 1969. Distribution of earthquakes in the New Guinea-Solomon Islands region. *Journal of Geophysical Research*, 74, 4290-4299.

Diamond, J. M. 1972. Biogeographic kinetics: estimation of relaxation times for avifaunas of southwest Pacific islands. *Proceedings of the National Academy of Sciences, U.S.A.* 69, 3199-3203.

Dickson, J. H. 1965. The effects of the eruption of 1961 on the vegetation of Tristan da Cunha. *Philosophical Transactions of the Royal Society of London*, B 249, 403-424.

Duffy, D. C. 1990. Seabirds and the 1982-1984 El Niño-Southern Oscillation. P. W. Glynn, ed.: *Global ecological consequences of the 1982-83 El Niño-Southern Oscillation* (Amsterdam: Elsevier), 395-415.

Dupon, J.-F. 1987. Les atolls et le risque cyclonique: le cas des Tuamotu. *Cahiers ORSTOM, Sciences humaines*, 23, 567-599; reprinted in *Bulletin de la Société d'Etudes océaniennes* 20 (10) [1987], 42-71.

Earle, M. D. 1975. Extreme wave conditions during Hurricane Camille. *Journal of Geophysical Research*, 80, 377-379.

Eaton, J. P., Richter, D. H. and Ault, W. U. 1961. The tsunami of May 23, 1960, on the island of Hawaii. *Bulletin of the Seismological Society of America* 51, 135-157.

Ellison, J. C. and Stoddart, D. R. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research*, 7, 151-165.

Emanuel, K. A. 1987. The dependence of hurricane intensity on climate. *Nature*, 326, 483-485.

Everingham, I. B. 1974. Large earthquakes in the New Guinea-Solomon Islands area, 1873-1972. *Tectonophysics*, 23, 323-338.

Eyre, L. A. and Gray, C. 1990. Utilization of satellite imagery in the assessment of the effect of global warming on the frequency and distribution of tropical cyclonic storms in the Caribbean, East Pacific and Australian regions. *Proceedings of the 23rd International Symposium on Remote Sensing of the Environment* (Bangkok, April 18-25, 1990), 365-375.

Fosberg, F. R. 1956. *Military Geography of the northern Marshalls*. Tokyo: H.Q. U.S. Army Forces Far East, Office of the Engineer, Intelligence Division. 320 pp.

Fosberg, F. R. 1963. The island ecosystem. F. R. Fosberg, ed.: *Man's place in the island ecosystem* (Honolulu: Bishop Museum Press), 1-6.

Fournier, F. 1960. *Climat et érosion: la rélation entre l'érosion du sol par l'eau et les précipitations atmosphériques.* Paris: Presses Universitaires de France. 201 pp.

Fridriksson, S. 1975. *Surtsey.* London: Butterworth. 198 pp.

Frith, C. B. 1976. A twelve-month field study of the Aldabran Fody, *Foudia eminentissima aldabrana. Ibis,* 118, 155-178.

Frith, D. W. 1979. A twelve month study of insect abundance and composition at various localities on Aldabra Atoll. *Philosophical Transactions of the Royal Society of London,* B 286, 119-126.

Galloway, R. W. and Löffler, E. 1972. Aspects of geomorphology and soils in the Torres Strait region. D. Walker, ed.: *Bridge and barrier: the natural and cultural history of Torres Strait* (Canberra: Australian National University, Research School of Pacific Studies, Department of Biogeography and Geomorphology), 11-28.

Giambelluca, T. W., Nullet, D. and Nullet, M. A. 1988. Agricultural drought on south-central Pacific islands. *Professional Geographer* 40, 404-415.

Gill, A. E. and Rasmusson, E. M. 1983. The 1982-83 climatic anomaly in the equatorial Pacific. *Nature,* 306, 229-234.

Glynn, P. W. 1990. Coral mortality and disturbances to coral reefs in the tropical eastern Pacific. P. W. Glynn, ed.: *Global ecological consequences of the 1982-83 El Niño-Southern Oscillation* (Amsterdam: Elsevier), 55-126.

Glynn, P. W. and Wellington, G. M. 1983. *Corals and coral reefs of the Galapagos Islands.* Berkeley: University of California Press. xvi, 330 pp.

Gornitz, V. 1991. Global coastal hazards from future sea level rise. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change)*, 89, 379-398.

Gornitz, V. and Lebedeff, S. 1987. Global sea-level changes during the past century. *Society of Economic Paleontologists and Mineralogists Special Publication* 41, 3-16.

Granger, O. 1990. *Natural disasters and social change: an eastern Caribbean perspective*. Oakland. 172 pp.

Gray, W. M. and Sheaffer, J. D. 1991. El Niño and QBO influences on tropical activity. M. H. Glantz, R. H. Latz and N. Nicholls, eds.: *Teleconnections linking worldwide climate anomalies: scientific basis and societal impact* (Cambridge: Cambridge University Press), 257-284.

Greenslade, P. J. M. 1968a. Island patterns in the Solomon Islands bird fauna. *Evolution*, 22, 751-761.

Greenslade, P. J. M. 1968b. The distribution of some insects of the Solomon Islands. *Proceedings of the Linnean Society of London*, 179, 189-196.

Greenslade, P. J. M. 1969. Insect distribution patterns in the Solomon Islands. *Philosophical Transactions of the Royal Society of London*, B 255, 271-284.

Grigg, R. W. and Maragos, J. E. 1974. Recolonization of hermatypic corals on submerged lava flows in Hawaii. *Ecology*, 55, 387-395.

Hansen, D. V. 1990. Physical aspects of the El Niño event of 1982-1983. P. W. Glynn, ed.: *Global ecological consequences of the 1982-83 El Niño-Southern Oscillation* (Amsterdam: Elsevier), 1-20.

Harmelin-Vivien, M. L. and Laboute, P. 1986. Catastrophic impact of hurricanes on atoll outer reef slopes in the Tuamotu (French Polynesia). *Coral Reefs*, 5, 55-62.

Hnatiuk, R. J. 1979. Temporal and spatial variations in precipitation on Aldabra. *Philosophical Transactions of the Royal Society of London* B 286, 25-34.

Hoffmeister, J. E., Ladd, H. S. and Alling, H. L. 1929. Falcon Island. *American Journal of Science*, (5) 18, 461-471.

Hopley, D. and Kinsey, D. W. 1988. The effect of a rapid short-term sea level rise on the Great Barrier Reef. G. I. Pearman, ed.: *Greenhouse: planning for climate change* (Melbourne: CSIRO Publications), 189-201.

Howard, R. A. 1962. Volcanism and vegetation in the Lesser Antilles, *Journal of the Arnold Arboretum*, 43, 279-314.

Ichiye, T. and Petersen, J. R. 1963. The anomalous rainfall of the 1957-58 winter in the equatorial central Pacific arid area. *Journal of the Meteorological Society of Japan*, 41- 172-182.

Jenkin, R. N. and Foale, M. A. 1968. An investigation of the coconut-growing potential of Christmas Island. *Land Resource Studies*, 4, 1-123, 1-113.

Juvik, J. O. and Austring, A. P. 1979. The Hawaiian avifauna: biogeographic theory in evolutionary time. *Journal of Biogeography* 6, 205-224.

Kennett, J. P. and Thunell, R. C. 1975. Global increase in Quaternary explosive vulcanism. *Science*, 187, 497-503.

Keys, J. E. 1963. The tsunami of 22 May 1960 in the Samoa and Cook Islands. *Bulletin of the Seismological Society of America*, 53, 1211-1227.

Knudson, K. E. 1964. *Titiana: a Gilbertese community in the Solomon Islands.* Eugene: University of Oregon, Department of Anthropology. 245 pp.

Kraus, E. B. 1955. Secular changes of tropical rainfall regime. *Quarterly Journal of the Royal Meteorological Society*, 81, 198-210.

Laboute, P. 1935. Evaluation dés degats causés par les passages des cyclones de 1982-1983 en Polynésie française sur les pentes externes des atolls de Tikehau et de Takapoto (Archipel des Tuamotu). *Proceedings of the 5th International Coral Reef Congress*, 3, 323-329.

Latter, J. H. 1981. Tsunamis of volcanic origin: summary of causes, with particular reference to Krakatoa 1883. *Bulletin of Volcanology*, 44.

Lea, D. 1973. Stress and adaptation to change: an example from the East Sepik District, New Guinea. H. Brookfield, ed.: *The Pacific in transition* (London: Arnold), 55-74.

Lessa, W. A. 1964. The social effects of Typhoon Ophelia (1960) on Ulithi. *Micronesica*, 1, 1-47.

Lister, J. J. 1890. A visit to the newly emerged Falcon Island, Tonga Group, south Pacific. *Proceedings of the Royal Geographical Society*, n.s. 12, 157-160.

Lukas, R., Hayes, S. P. and Wyrtki, K. 1984. Equatorial sea level response during the 1982-1983 El Niño. *Journal of Geophysical Research*, 89, 10425-10430.

MacArthur, R. H. and Wilson, F. O. 1967. *The theory of island biogeography*. Princeton: Princeton University Press. xi, 203 pp.

MacCaughey, V. 1917. Vegetation of Hawaiian lava flows. *Botanical Gazette*, 64, 386-420.

Macdonald, G. A., Abbott, A. T. and Peterson, F. L. 1983. *Volcanoes in the sea*. Honolulu: University of Hawaii Press. 2nd edition.

Marshall, C. 1956. Long term meteorological variations and their effects on land uses in small south Pacific islands. *Proceedings of the 8th Pacific Science Congress*, 2A, 1129-1135.

McLean, R. F. 1980. Spatial and temporal variability of external physical controls on small island ecosystems. H. C. Brookfield, ed.: *Population-environment*

relations in tropical islands: the case of eastern Fiji (*MAB Technical Notes*, 13), 149-175.

McNutt, M. and Menard, H. W. 1978. Lithospheric flexure and uplifted atolls. *Journal of Geophysical Research*, 83, 1206-1212.

Meade, R. H. and Emery, K. O. 1971. Sea level as affected by river runoff. *Science*, 173, 425-428.

Melson, W. G., Jarosewich, E. and Lundquist, C. A. 1970. Volcanic eruption at Metis Shoal, Tonga, 1967-68: description and petrology. *Smithsonian Contributions to Earth Science*, 4, 1-18.

Miller, D. L. R. and Mackenzie, F. T. 1988. Implications of climate change and associated sea-level rise for atolls. *Proceedings of the 6th International Coral Reef Symposium*, 3, 519-522.

Milton, D. 1974. Some observations of global trends in tropical cyclone frequencies. *Weather*, 29, 267-270.

Miyagi, M., Shimabukuro, S. and Mezaki, S. 1980. *A geographical guide to Okinawa*. Naha: University of the Ryukyus. 95 pp.

Montaggioni, L. F. 1979. Le problème de l'absence de hauts stationnements marins d'age holocène dans l'archipel des Mascareignes. *Comptes rendus hebdomadaires des Séances de l'Academie des Sciences*, Paris, 288, 1591-1594.

Moore, J. G. and Moore, G. W. 1984. Deposit from a giant wave on the island of Lanai, Hawaii. *Science*, 226, 1312-1315.

Mörner, N.-A. 1971. Eustatic and climatic oscillations. *Arctic and Alpine Research*, 3, 167-171.

Neumann, C. J., Cry, G. W., Caso, E. L. and Javinen, B. R. 1981. *Tropical cyclones of the North Atlantic Ocean, 1871-1980*. Asheville, N.C.: U.S Department of Commerce, NOAA–National Climatic Center. 174 pp.

Niering, W. S. 1963. Terrestrial ecology of Kapingamarangi Atoll, Caroline Islands. *Ecological Monographs*, 33, 131-160.

Nullett, D. 1987. Water balance of Pacific atolls. *Water Resources Bulletin*, 23, 1125-1132.

Nullet, D. and Giambucella, T. W. 1988. Risk analysis of seasonal agricultural drought on low Pacific islands. *Agricultural and Forest Meteorology*, 42, 229-239.

Nunn, P. D. 1980. Recent environmental changes on Pacific islands. *Geographical Journal* 156, 125-140.

Nunn, P. D. 1990. Coastal processes and landforms of Fiji and their bearing on Holocene sea-level changes in the south and west Pacific. *Journal of Coastal Research*, 6, 279-310.

Nunn, P. D. 1991. Keimami sa vakila na liga ni Kalou (Feeling the hand of God): human and nonhuman impacts on Pacific island environments. *Occasional Papers East-West Environment and Policy Institute, East-West Center*, 13, i-viii, 1-68.

Oberdorfer, J. A. and Buddemeier, R. W. 1988. Climate change: effects on reef island resources. *Proceedings of the 6th International Coral Reef Symposium* 3, 523-527.

Oguntoyinbo, J. S. 1966. Evapotranspiration and sugarcane yields in Barbados. *Journal of Tropical Geography*, 22, 38-48.

Pain, C. F. and Bowler, J. M. 1973. Denudation following the December 1970 earthquake at Madang, Papua New Guinea. *Zeitschrift für Geomorphologie*, N.F. Supplbd. 18, 92-104.

Parthasarathy, B. and Dhar, O. N. 1974. Secular variations of regional rainfall over India. *Quarterly Journal of the Royal Meteorological Society*, 100, 245-257.

Patel, J. S. and Anandan, A. P. 1936. Rainfall and yield in the coconut. *Madras Agricultural Journal*, 24, 5-15.

Paulay, G. 1990. Effects of late Cenozoic sea-level fluctuations on the bivalve faunas of tropical oceanic islands. *Paleobiology*, 16, 415-434.

Peake, J. F. 1969. Patterns in the distribution of Melanesian land Mollusca. *Philosophical Transactions of the Royal Society of London*, B 255, 285-306.

Peake, J. F. 1971. The evolution of terrestrial faunas in the western Indian Ocean. *Philosophical Transactions of the Royal Society of London*, B 260, 581-610.

Philander, S. G. H. 1989. El Niño and La Niña. *American Scientist, 77*, 451-459.

Pirazzoli, P. A. 1986. Secular trends of relative sea-level (RSL) records indicated by tide-gauge records. *Journal of Coastal Research,* Special Issue, 1, 1-26.

Pirazzoli, P. A. 1989. Present and near-future global sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change)*, 1, 241-258.

Pirazzoli, P. A. and Montaggioni, L. 1986. Late Holocene sea level changes in the northwest Tuamotu Islands, French Polynesia. *Quaternary Research,* 25, 350-368.

Pirazzoli, P. A. and Montaggioni, L. F. 1988a. The 7,000 yr sea-level curve in French Polynesia: geodynamic implications for midplate volcanic islands. *Proceedings of the 6th International Coral Reef Symposium,* 3, 467-472.

Pirazzoli, P. A. and Montaggioni, L. F. 1988b. Holocene sea-level changes in French Polynesia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 68, 153-175.

Pirazzoli, P. A., Montaggioni, L. F., Delibrias, G., Faure, G. and Salvat, B. 1985. Late Holocene sea-level changes in the Society Islands and the northwest Tuamotu atolls. *Proceedings of the 5th International Coral Reef Congress,* 3, 131-136.

Pirazzoli, P. A., Montaggioni, L. F., Salvat, B., and Faure, G. 1988. Late Holocene sea level indicators from twelve atolls in the central and eastern Tuamotus (Pacific Ocean). *Coral Reefs*, 7, 57-68.

Pirazzoli, P. A., Radtke, U., Hantoro, W. S., Jouannic, C., Hoang, C. T., Causse, C. and Borel Best, M. 1991. Quaternary raised coral-reef terraces on Sumba Island, Indonesia. *Science*, 252, 1834-1836.

Potts, D. C. 1983. Evolutionary disequilibrium among Indo-Pacific corals. *Bulletin of Marine Science*, 33, 619-632.

Potts, D. C. 1984. Generation times and the Quaternary evolution of reef-building corals. *Paleobiology*, 10, 48-58.

Potts, D. C. 1985. Sea-level fluctuations and speciation in Scleractinia. *Proceedings of the 5th International Coral Reef Congress* 4, 127-132.

Quinn, D. B., Dopf, D. O., Short, K. S., Kuo-Yang, R. T. W. 1978. Historical trends and statistics of the Southern Oscillation, El Niño, and Indonesian droughts. *Fisheries Bulletin*, 76, 663-678.

Quinn, W. H., Neal, V. T. and Antunez de Mayolo, S. E. 1987. El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research*, 92, 14449-14461.

Rasmusson, E. M. 1983. El Niño: the great equatorial Pacific Ocean warming event of 1982-83. *Weatherwise*, 36, 166-175.

Rasmusson, E. M. 1985. El Niño and variations in climate. *American Scientist*, 73, 168-177.

Richards, A. F. 1958. Transpacific distribution of floating pumice from Isla San Benedicto, Mexico. *Deep-Sea Research*, 5, 29-35.

Richards, A. F. and Dietz, R. S. 1956. Eruption of Barcéna volcano, San Benedicto Island, Mexico. *Proceedings of the 8th Pacific Science Congress*, 2, 157-176.

Rosenzweig, M. L. 1968. Net primary productivity of terrestrial communities: production from climatological data. *American Naturalist*, 102, 67-74.

Rotondo, G. M., Springer, V. G., Scott, G. A. J., and Schlanger, S. O. 1981. Plate movement and island integration—a possible mechanism in the formation of endemic biotas, with special reference to the Hawaiian Islands. *Systematic Zoology*, 30, 12-21.

Rougerie, F. 1991. Le blanchissement des coraux de l'été 1991: phénomène régional où signal d'alarme planétaire? *Tahiti Pacifique*, 1 (6), 20-23.

Sachet, M.-H. 1955. Pumice and other extraneous volcanic materials on coral atolls. *Atoll Research Bulletin*, 37, 1-27.

Sachet, M.-H. 1957. Climate and meteorology of the Gilbert Islands. *Atoll Research Bulletin*, 60, 1-4.

Schlanger, S. O. and Gillett, G. W. 1976. A geological perspective on the upland biota of Laysan Atoll (Hawaiian Islands). *Biological Journal of the Linnean Society*, 8, 205-216.

Scholl, D. W., Craighead, F. C. and Stuiver, M. 1969. Florida submergence curve revised: its relation to coastal sedimentation rates. *Science*, 163, 562-564.

Scholl, D. W. and Stuiver, M. 1967. Recent submergence of southern Florida: a comparison with adjacent coasts and other eustatic data. *Geological Society of American Bulletin*, 78, 437-454.

Schreiber, E. A. and Schreiber, R. W. 1989. Insights into seabird ecology from a global "natural experiment". *National Geographic Research*, 5, 64-81.

Schreiber, R. W. and Schreiber, E. A. 1984. Central Pacific seabirds and the El Niño-Southern Oscillation: 1982-1983 perspectives. *Science*, 225, 713-716.

Schwartz, M. L. 1967. The Bruun theory of sea level rise as a cause of shore erosion. *Journal of Geology*, 75, 76-91.

Scoffin, T. P. and Stoddart, D. R. 1978. The nature and significance of microatolls. *Philosophical Transactions of the Royal Society of London*, B 284, 99-122.

Self, S. and Rampino, M. R. 1981. The 1883 eruption of Krakatau. *Nature*, 294, 699-704.

Service d'Etat de Météorologie, Polynésie française. 1990. *Vents, cyclones, houles, pluies exceptionnelles en Polynésie française*. Papeete: Service d'Etat de Météorologie.

Shepard, F. P., Macdonald, G. A. and Cox, D. C. 1950. The tsunami of April 1, 1946. *Bulletin of the Scripps Institution of Oceanography* 5, 391-527.

Simkin, T. and Fiske, R. S. 1983. *Krakatau 1883: the explosion and its effects*. Washington, D.C.: Smithsonian Institution Press. 464 pp.

Simpson, B. B. 1974. Glacial migrations of plants: island biogeographical evidence. *Science*, 185, 698-700.

Skottsberg, C. 1941. Plant succession on recent lava flows in the island of Hawaii. *Göteborgs Kungl. Vetenskaps och Vitterhets Samhälles Handlingar*, B 1, 1-32.

Smith, G. W. 1966. The relation between rainfall, soil water and yield of copra on a coconut estate in Trinidad. *Journal of Applied Ecology*, 3, 117-125.

Smith, I. 1962. *Climatic control of distribution and cultivation of sugarcane*. McGill University Ph.D. thesis.

Sousa, W. P. 1984. The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* 15, 353-391.

Spate, O. H. K. 1963. Islands and men. F. R. Fosberg, ed.: *Man's place in the island ecosystem* (Honolulu: Bishop Museum Press), 253-264.

Stewart, J. 1973. Rainfall trends in north Queensland. *James Cook University of North Queensland, Department of Geography, Monograph Series*, 4, i-xiv, 1-197.

Stewart, R. W., Kjerfve, B., Milliman, J. and Dwivedi, S. N. 1990. Relative sea-level change: a critical evaluation. *UNESCO Reports in Marine Science*, 54, 1-22.

Stoddart, D. R. 1969. Climatic geomorphology: review and re-assessment. *Progress in Geography*, 1, 159-222.

Stoddart, D. R. 1971a. Rainfall on Indian Ocean coral islands. *Atoll Research Bulletin*, 147, 1-21.

Stoddart, D. R. 1971b. Coral reefs and islands and catastrophic storms. J. A. Steers, ed.: *Applied coastal geomorphology* (London: Macmillan), 155-197.

Stoddart, D. R. 1971c. Environment and history in Indian Ocean reef morphology. *Symposia of the Zoological Society of London*, 28, 3-38.

Stoddart, D . R. 1972. Catastrophic damage to coral reef communities by earthquake. *Nature*, 239, 51-52.

Stoddart, D. R. 1975. Vegetation and floristics of the Aitutaki motus. *Atoll Research Bulletin*, 190, 87-116.

Stoddart, D. R. 1976. Crisis and continuity in the reef community. *Micronesica*, 12, 1-9.

Stoddart, D. R. and Mole, L. U. 1977. Climate of Aldabra Atoll. *Atoll Research Bulletin*, 202, 1-21.

Stoddart, D. R. 1978. The Great Barrier Reef and the Great Barrier Reef Expedition 1973. *Philosophical Transactions of the Royal Society of London*, A 291, 5-22.

Stoddart, D. R. 1983. Spatial and temporal variability of rainfall on Aldabra Atoll. *Atoll Research Bulletin* 273, 223-246.

Stoddart, D. R. 1990. Coral reefs and islands and predicted sea-level rise. *Progress in Physical Geography*, 14, 521-536.

Stoddart, D. R. 1992. Biogeography of the tropical Pacific. *Pacific Science*, 46, 276-293.

Stoddart, D. R. and Fosberg, F. R. 1981. Topographic and floristic change, Dry Tortugas, Florida, 1904-1977. *Atoll Research Bulletin*, 253, 1-55.

Stoddart, D. R. and Mole, L. U. 1977. Climate of Aldabra Atoll. *Atoll Research Bulletin* 202, 1-21.

Stoddart, D. R. and Scoffin, T. P. 1983. Phosphate rock on coral reef islands. A. S. Goudie and K. Pye, eds.: *Chemical sediments and geomorphology* (London: Academic Press), 369-400.

Stoddart, D. R. and Walsh, R. P. D. 1979. Long-term climatic change in the western Indian Ocean. *Philosophical Transactions of the Royal Society of London*, B 286, 11-23.

Taylor, J. D. 1978. Faunal response to the instability of reef habitats: Pleistocene molluscan assemblages of Aldabra Atoll. *Palaeontology*, 21, 1-30.

Taylor, F. W., Edwards, R. L., Wasserburg, G. J. and Frohlich, C. 1990. Seismic recurrence intervals and timing of aseismic subduction inferred from emerged corals and reefs of the central Vanuatu (New Hebrides) frontal arc. *Journal of Geophysical Research*, 95, 393-408.

Taylor, F. W., Frohlich, C., Lecolle, J. and Strecker, M. 1987. Analysis of partially emerged corals and reef terraces in the central Vanuatu arc: comparison

of contemporary coseismic and nonseismic with Quaternary vertical movements. *Journal of Geophysical Research*, 92, 4905-4933.

Taylor, F. W., Jouannic, C., Gilpin, L., and Bloom, A. L. 1981. Coral colonies as monitors of change in relative level of the land and sea: applications to vertical tectonism. *Proceedings of the 4th International Coral Reef Symposium*, 2, 485-492.

Taylor, J. D., Braithwaite, C. J. R., Peake, J. F. and Arnold, E. N. 1979. Terrestrial faunas and habitats of Aldabra during the late Pleistocene. *Philosophical Transactions of the Royal Society of London*, B 286, 47-66.

Taylor, R. C. 1973. An atlas of Pacific islands rainfall. *Hawaii Institute of Geophysics Data Report*, 25.

Thomas, W. L., Jr. 1963. The variety of physical environments among Pacific islands. F. R. Fosberg, ed.: *Man's place in the island ecosystem* (Honolulu: Bishop Museum Press), 7-37.

Valle, C. A., Cruz, F., Cruz, J. B., Merlen, G and Coulter, M. C. 1987. The impact of the 1982-1983 El Niño-Southern Oscillation on seabirds in the Galapagos Islands, Ecuador. *Journal of Geophysical Research*, 92, 14437-14444.

Vitousek, J. M. 1963. The tsunami of 22 May 1960 in French Polynesia. *Bulletin of the Seismological Society of America*, 53, 1229-1236.

Waddell, E. 1973. Raiapu Enga adaptive strategies: structure and general implications. H. Brookfield, ed.: *The Pacific in transition* (London: Arnold), 25-54.

Walsh, R. P. D. 1977. Changes in the tracks and frequency of tropical cyclones in the Lesser Antilles from 1650 to 1975 and some geomorphological and ecological implications. *Swansea Geographer*, 15, 4-11.

Walsh, R. P. D. 1984. Climate of the Seychelles. D. R. Stoddart, ed.: *Biogeography and ecology of the Seychelles Islands* (The Hague: W. Junk), 39-62.

Walsh, R. P. D. and Reading, A. J. 1991. Historical changes in tropical cyclone frequency within the Caribbean since 1500. R. Glaser and R. P. D. Walsh, eds.: *Historical climatology in different climatic zones* (*Würzburger Geographische Arbeiten*, 80), 199-240.

Weaver, D. C. 1968. The hurricane as an economic catalyst. *Journal of Tropical Geography*, 27, 66-71.

Wendland, W. M. 1977. Tropical storm frequencies related to sea surface temperatures. *Journal of Applied Meteorology* 16, 477-481.

Wheatcraft, S. W. and Buddemeier, R. W. 1981. Atoll island hydrology. *Ground Water*, 19, 311-320.

Whitehead, D. R. and Jones, C. E. 1969. Small islands and the equilibrium theory of insular biogeography. *Evolution*, 23, 171-179.

Whitmore, T. C. 1974. Change with time and the role of cyclones in tropical rain forest on Kolombangara, Solomon Islands. *Commonwealth Forestry Institute Papers*, 46.

Wiens, H. J. 1962. *Atoll environment and ecology*. New Haven: Yale University Press. 532 pp.

Williams, E. H., Goenaga, C. and Vicente, V. 1987. Mass bleachings on Atlantic coral reefs. *Science*, 237, 877-878.

Williamson, M. 1989. The MacArthur and Wilson theory today: true but trivial. *Journal of Biogeography*, 16, 3-4.

Woodley, J. D. and nineteen other authors. 1981. Hurricane Allen's impact on Jamaican coral reefs. *Science*, 214, 749-755.

Woodroffe, C. D. 1989. *Salt water intrusion into groundwater: an assessment of effects on small island states*. Small States Conference on Sea-level Rise (Male, Maldive Islands, 12-18 November 1989), 33 pp.

Woodroffe, C. D. and Grinrod, J. 1991. Mangrove biogeography: the role of Quaternary environmental and sea-level change. *Journal of Biogeography*, 18, 479-492.

Woodroffe, C. D., McLean, R. F., Polach, H. and Wallensky, E. 1990a. Sea level and coral atolls: late Holocene emergence in the Indian Ocean. *Geology*, 18, 62-66.

Woodroffe, C. D., Stoddart, D. R., Spencer, T., Scoffin, T. P., and Tudhope, A. W. 1990b. Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs*, 9, 31-39.

Yamaguchi, M. 1975. Sea level fluctuations and mass mortalities of reef animals in Guam, Mariana Islands. *Micronesica*, 11, 227-243.

Yamashita, A. C. 1965. Attitudes and reactions to Typhoon Karen (1962) in Guam. *Micronesica*, 2, 15-23.

ATOLL RESEARCH BULLETIN

NO. 357

NUKUTIPIPI ATOLL, TUAMOTU ARCHIPELAGO; GEOMORPHOLOGY, LAND AND MARINE FLORA AND FAUNA AND INTERRELATIONSHIPS

BY

F. SALVAT AND B. SALVAT

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

FIGURES

TABLES

PLATES

Plate 22 : Old conglomerate remnants of the south rim of Nukutipipi atoll, separating submerged reef flat (rigth) and sand platform lagoon (left). Dating gives 4395 ± 95 years B.P. Ref. plate : 1982 / 8-13, MM. J.A. Madec and R. Wan).

Plate 23 : Remnant of fossil algal crest on the south rim of Nukutipipi. Boundstone sample 1 m above low tide level was dated 3560 ± 100 years B.P. (Ref. plate : 1982 / 8-19, M. J. A. Madec).

Plate 24 : Dead branches of *Acropora* constituting dome patch reefs in the lagoon. *Chama asperella* population fixed at the tip of branches (Ref. plate : 1988 / 7-19).

Plate 25 : Living and dead *Chama asperella* populations from the dome patch reef of the Nukutipipi lagoon (Ref.plate : 1988 / 7-20).

NUKUTIPIPI ATOLL, TUAMOTU ARCHIPELAGO: GEOMORPHOLOGY, LAND AND MARINE FLORA AND FAUNA AND INTERRELATIONSHIPS

by

FRANCINE SALVAT (1) AND BERNARD SALVAT (1)

ABSTRACT

Nukutipipi atoll (5 km2), of volcanic origin 16-17 million years old on the Pitcairn (hot spot) Hereheretue line, presents a land flora and fauna of low diversity but with a *Pisonia* forest and hundreds of resident red-tailed tropic birds. Nukutipipi suffered from the 1983 hurricanes : destruction of vegetation and motu as well as sand lagoon mollusc populations. The north and south rims present original geomorphological structures. Lagoon without patch reefs reaching the surface is characterised by dome patch reefs all constituted of dead *Acropora* with few scleractinian and mollusc species, but an important algae coverage. All these characteristics indicate the precariousness on a time scale of such a so tiny atoll, land and marine, with a closed lagoon.

INTRODUCTION

Nukutipipi atoll is one of the tiniest low-lying islands of the Tuamotu archipelago and in the world (with a maximum length of some 3,5 km and a surface area of about 5 km^2).

It lies within two other small atolls (Anu Anunaro and Anu Anurunga), all three known as the Duke of Gloucester Islands, at 20-21° south latitude and 143-144° west longitude. These islands are in the southern central part of the Tuamotu archipelago (figure 1) and lie 700 km off Society Island Tahiti, to the north west, and 857 km off Mangareva, Gambier Islands, in the south east. Although no more 40 km distant from each other, they are separated by an ocean as deep as 2,000 m.

Observations on Nukutipipi atoll which we are reporting were mainly in November 1988 but also previously in August 1982 and July 1986. We had at our disposal an aerial cover of the entire atoll from "Aéronautique navale française (Ref. VTTA ANF/ 26/65, 278 CEP/EM/DPS/SC) 11 th July 1965 - 37 prints - 1/5000 ème).

---

(1) Laboratoire de Biologie Marine et Malacologie, Ecole Pratique des Hautes Etudes, URA CNRS 1453, Centre de Biologie et d'Ecologie Tropicale et Méditerranéenne, Université de Perpignan, 66860 Perpignan cedex, France.
Centre de l'Environnement d'Opunohu, BP 1013 Papetoai, Moorea, Polynésie française.

Manuscript received 23 October 1991; revised 15 December 1991

DISCOVERY AND HUMAN ACTIVITIES :

The atoll was discovered by Carteret on 12th July, 1767, observation being reported by Emory (1939) : "On the 12th, we fell in with two more small islands, which were covered with green trees, but appeared to be uninhabited. We were close in with the southernmost (Nukutipipi), which proved to be a slip of land in the form of a half moon, low, flat, and sandy : from the south end of it a reef runs out to a distance of about half a mile, on which the sea breaks with great fury. We found no anchorage, but the boat landed. It had a pleasant appearance, but afforded neither vegetables nor water ; there were, however, many birds upon it, so tame that they suffered themselves to be taken by hand. The other island very much resembles this, and is distant from it about five or six leagues." On 1841, the atoll was visited by Ringgold of the Wilkes Expedition. On the 6th January, 1841 he identified Nukutipipi, using for the first time the native name of the atoll, as the atoll previously named by Turnbull as Margaret's island during his expedition. Ringgold mentions (Emory, 1939) : "On the 6th, Nukutipipi or Margaret's island was made, a small round lagoon island, two miles in circumference, high and well wooded on the north side, with a flat submerged reef on the southeast and east sides".

Nukutipipi was an uninhabited low-lying island covered with natural primitive vegetation. Between 1911 and 1926 (date not precisely known) the atoll was a concession of the "Société Commerciale de l'Océanie" and part of the atoll was reclaimed and planted with coconut trees. After failure of the Société the atoll was sold to MM. Cassiau and Pomel in 1935, then to M. Gonin, then to M. Madec in 1980, the present land owner of the atoll. In 1982, an airfield was inaugurated. On 1983 two violent hurricanes (Orama and Veena) struck Nukutipipi destroying almost all the coconut plantation and all bungalows. New plantation and reconstruction took place in 1985. In 1991 Nukutipipi is to be sold to a Japanese Society.

No scientific observation nor contribution has previously been published on Nukutipipi related to its remote position in the archipelago. However, in the vicinity of the Duke of Gloucester islands numerous papers have been published on Mururoa - 430 km on the east - (see Chevalier et ali., 1968 and Renon, 1989), on Fangataufa - near Mururoa - (see Salvat, 1970), and on Hereheretue - 210 km to the west (see Richard, 1970).

CLIMATE :

Nukutipipi enjoys a hot and humid tropical oceanic climate. It lies in the south tropical convergence zone between two anticyclonic zones. The first of these on Easter Island brings heat and humidity along with east and north-east trade winds. The second, on Kermadec, brings fresh air along with south-east trade winds. The frontier between these two anticyclonic zones shifts to the north of Nukutipipi during the austral winter and to the south during the austral summer. Lacking climatic information specific to the atoll, we refer to the nearby atoll of Mururoa - 1° latitude more - (Renon, 1989). Figure 2 gives monthly mean temperatures of air and sea, and monthly precipitation and evaporation. Air temperature is between 22 and 27°C. There are more than 2,600 hours sunshine during the year (average of 7 h 30 per day), and about 12 storm days per year. If hurricanes are unusual in French Polynesia (the last periods go back to 1874, then 1903-1906), no less than 6 occured between december 1982 and april 1983, two of them striking the atoll (Orama in February and Veena in April).

ORIGIN OF THE ISLAND :

According to plate tectonic theory, Nukutipipi atoll - as all French Polynesian islands (118 islands of which 84 are atolls) - is affected by two movements : drift of the Pacific plate to the west north-west and subsidence. Volcanic migration rate have been estimated between 10.4 and 12.7 cm/year for different Pacific Island chains (Spencer, 1989). According to Brousse (1985) the sequence Gambier - Mururoa has been affected by a migration rate of 10.7 - 11 cm/year. Subsidence is about 0.1 cm per year (or 10 cm per century).

The floor near the Duke of Gloucester islands is 50 millions years old, moving to the west-north-west since its creation at the East Pacific Ridge. It is currently maintained that the Tuamotu islands are the remants of a micro continent which emerged on the west side of the East Pacific Rise 40 to 63 million years ago. All other archipelagoes of French Polynesia (Society, Marquesas and Austral) are of hot spot volcanic activity (Scott and Rotondo, 1982). However, according to Okal and Cazenave (1985) many islands of the south Tuamotu and Gambier islands are related to hot spot activity. Nukutipipi is part of a sequence from Pitcairn (vicinity of the hot spot) to Hereheretue atoll. Some volcanism has been dated along this line : Gambier is 5 to 7 millions years old. Mururoa is 11 millions years old. According to distance from the hot spot and with these values and the speed of drift, Nukutipipi at 1,500 km from Pitcairn is estimated to be as old as 16-17 millions years. Figure 3 shows the distribution from Pitcairn to Hereheretue.

BRIEF DESCRIPTION OF THE ATOLL :

Nukutipipi is half moon shaped and oriented west-north-west and east-south-east, with its long axis of 3.5 km and small axis of approximatly 2 km. Two little islets (motu) of different length constitute the north and curved rim of the atoll : the north-west motu is 673 m long and the north motu is 2,745 m long. They are separated by a narrow channel (hoa) communicating ocean and lagoon waters, which is maximally 150 m wide and 1 m deep. The south rim of the atoll is a submerged reef where ocean water enters the lagoon, which is 1.500 m wide and no more than 2 m deep. The lagoon consist of a shallow platform, 0 to 2 metres deep, well developed on the south submerged rim, surrounding a deeper part (about 100 hectares, 17 m maximum depth). No patch reef rises up from the lagoon floor to the surface. When trade winds blow from the south or from the east, ocean waves break on the algal crest of the south rim and die towards the lagoon ; lagoon waters exit to the ocean via the hoa. Figure 4 shows a map of the atoll and two sections along the longitudinal and transversal axis.

The tidal range is between 20 and 40 cm according to neap or spring tides but meteorological and oceanographical conditions have more effect on the lagoonal water level than the tide. Salinity in the region is 36‰ throughout the year and sea surface temperature between 23 and 27°5 C.

LAND FLORA AND FAUNA

Flora and fauna of low-lying islands are poor in species diversity due to very low habitat diversity. All species have to be adapted to oceanic conditions and to carbonate soils. As islanders all species may have reached the island by themselves (anemochory, hydrochory or zoochory) or introduced by man. The remoteness of an island in relation to

others in the vicinity, the size of an island to enable species to expand and the inhabitance or not by man, are some of the ecological factors of major importance which help explain the composition of flora and fauna. The Tuamotu atolls are more than 5,000 km from the American and Australian continents, and Nukutipipi, one of the 76 low-lying islands lying to the south of the archipelago, is remote. The nearest atoll to the Duke of Gloucester islands (Nukutipipi, Anu Anuraro and Anu Anurunga), Hereheretue, lies 200 km to the West. Nukutipipi was uninhabited either by native polynesian or since the beginning of the century, except for a temporary period for coprah or pearl oyster harvest (no more than a few persons). We offer a comparative description of the flora and fauna of Nukutipipi based upon our knowledge of some other atolls in the Tuamotu group.

FLORA :

A total of 21 species have been collected and identified (some with the assistance of Florence, Orstom, Tahiti) and are listed in Table A. In view of to the small size of the two islets (motu) no tree or shrub escaped our inventory. So poor a flora is composed of very common plants found on atolls both in Polynesia and Micronesia (Fosberg, 1990) and there are no endemic species. Nevertheless, some comments are pertinent : on certain Tuamotu atolls more species were reported : 48 on Fangataufa (Jolinon, 1989), 39 on Rangiroa and 37 on Takapoto (Florence, 1986), as well as in the Society Islands : 48 on Tupai and 44 on Tetiaroa (Florence, 1986) but fewer on Scilly : 25-30 (Sachet, 1983). Comparison with Fangataufa flora shows that if all trees and shrubs on this atoll are also found on Nukutipipi, the opposite is not true. Four species exist on Nukutipipi but are absent from Fangataufa. The first is a very important one : *Pisonia grandis*, a tall tree which is the major element of the native vegetation (Fosberg, 1990) before being be cleared for coconut plantations. The absence of *Pisonia grandis* on Fangataufa is unexplained, as we note that there were only a few coconut palms before human settlement (1965) for the purpose of nuclear experiments, as is the situation today. The three other species have been introduced to Nukutipipi for food or ornament *(Artocarpus altilis, Musa troglodytorum* and *Gardenia taitensis*) and not on Fangataufa.

VEGETATION :

The largest motu consists of a 10 hectare primitive forest, the centre part being constituted of *Pisonia grandis, Pandanus tectorius, Guettarda speciosa* and some rare *Cocos nucifera.* Under the trees, and specially in some clearings, grow *Portulaca lutea, Laportea ruderalis* and *Lepidium bidentatum.* The ocean edge of this vegetation is mainly *Argusia argentea, Suriana maritima* and *Scaevola taccada* with tufts (or wisps) of *Lepturus repens* and *Heliotropium anomalum.* In some places *Triumfetta procumbens* entirely covers the sand from the beach to the primitive vegetation. The lagoon edge is dominated by *Scaevola, Argusia, Pandanus, Guettarda* and *Cocos.* The remains of the largest motu is a coconut plantation. About 200 coconut trees survived the 1983 cyclones. Since that time many thousands of coconut have been planted with about a thousand *Casuarina equisetifolia.* Food and ornamental species occurred near the bungalows on the lagoon edge of the largest motu.

The vegetation of the little motu, almost completely destroyed by the cyclones with no more than 50 surviving coconuts was recovering well in 1989. There was no *Pisonia* on this motu and dominant species are *Guettarda* and the massive shrub *Scaevola. Pemphis acidula* occurs only near the hoa.

LAND CRUSTACEANS AND REPTILES OF NUKUTIPIPI :

We did not collect any land invertebrates except for some land crabs. Only one *Grapsidae* was present but not abundant : *Geograpsus grayi. Cardisoma carnifex,* usually very common near the littoral where it digs deep burrows, is totally absent from the atoll. Four species of hermit crab where collected : *Aniculus aniculus,* a small species inhabiting small gastropod shells *(Muricidae, Cerithiidae),* and 3 larges species inhabiting *Turbo* shells *(Turbinidae)* and whose distinction can be made by their colours : *Coenobita perlatus* (red), *Coenobita brevimanus* (violet) and *Coenobita spinosus* (black). Due to the heavy mortality of *Turbo setosus* by cyclones (gastropods being torn away from the algal crest of the outer reef and deposited in the motu) and the abundance of shelter, the hermit crabs were very abundant.

Reptiles, including the green turtle - *Chelonia mydas* - which lays its eggs on the beaches of the atoll, are of special interest due to recent discovery of lizards which are parthenogenic. Presence or absence of species, parthenogenic or not, parasitised or not with competition between them on any atoll is a matter of biogeography (Blanc et Ineich, 1985 ; Ineich, 1987 and 1989 ; Bertrand et Ineich, 1989). Three species of Scincidae [*Emoia pheonura* (Ineich, 1987), *Cryptoblepharus poecilopleurus* (Wiegman, 1835), *Lipinia noctura* (Lesson, 1826)] and two species of Gekkonidae [*Lepidodactylus lugubris* (Dumeril and Bibron, 1836) - parthenogenic species - and *Gehyra oceanica* (Lesson, 1830)] have been collected.

BIRDS OF NUKUTIPIPI :

On discovering of the atoll, 1767, Carteret was impressed by "many birds, so tame that they suffered themselves to be taken by hand". Nukutipipi is the island of the Red-tailed tropicbird, *Phaethon rubricauda,* which nests on the sand, along with others species of marine birds.

Ten species have been checked (observations in June, August and November), 8 are marine and 2 are terrestrial birds. These are listed in Table B. The Reef Heron, *Egretta sacra* both black and white, together whith the only warbler found on atolls, the Long-billed Warbler, *Acrocephalus caffer,* form the two terrestrial avifauna of the atoll. One may note that after the cyclones of 1983 only one individual of this last species remained in 1988.

Visiting marine birds include the Wandering Tattler, *Tringa incana,* and the Bristle-Thighed curlew, *Numenius tahitensis,* with its long curved beak. Both these migrators from Alaska are present all the year round on Nukutipipi reefs. However, in November 1988, the most important populations of birds were nesting marine species except for Frigates, *Fregata minor.* Only a few specimens of this species occur in the atoll, with some others visiting from time to time, sometimes for the evening, from Anu Anurunga, the nearby atoll. All these nesting marine birds are permanently on the atoll : *Phaethon rubricauda* is the most abundant (many hundreds). Tern *(Sterna fuscata* or *Sterna lunata),* White Tern *(Gygis alba),* Black Noddy *(Anous tenuirostris)* and hundreds of Red-footed Booby *(Sula sula)* are the other species.

All recorded species are known in French Polynesia (Holyoak et Thibault, 1984) By comparison with Fangataufa atoll (Thibault, 1987), we point out the absence on Nukutipipi of *Phaethon lepturus* (White tailed Tropic Bird), of *Sula leucogaster* (Blue-footed Booby), of *Pluvialis dominica* (Lesser Golden Plover) and of *Sterna bergii* (Crested Terns). No introduced species to French Polynesia are present on Nukutipipi (Thibault and Guyot, 1988), neither *Acridotheres tristis* (Indian Mynah) nor *Columba livia,* respectively introduced on Gambier islands and Mururoa atoll.

No cats, dogs, pigs or other mammals are found in the atoll and the past land-owner, Mr. Madec, was very sensitive to the natural ecosystem of the island, remaining vigilent about introductions. *Rattus exulans* is present.

REEFS : GEOMORPHOLOGY AND COMMUNITIES

The preliminary description of Nukutipipi (see introduction) defines 3 units between the ocean and the land or the lagoon - A) islet reefs - B) submerged reef - C) hoa.

ISLET REEFS :

These reefs, facing to the ocean, back on to the motu with or without vegetation but nevertheless back on to the emerged part of the atoll rim. Such are the reefs back to the two motu. They have been prospected for geomorphology and communities along 8 transects from the reef front where ocean waves are breaking to the beach leading to the vegetation of the motu. These transects (A to H) are shown on figure 5 with a schematic representation on figure 6 of different geomorphological units.

The largest of these transects, A : 250 metres, backs on to the little motu. Other reefs are no more than 150-180 metres between the reef front and vegetation. The outer slope has not been prospected.

<u>The reef front</u> is an algal crest on all transects apart from on A, the north-west part of the rim where hydrodynamism is less important. Opposite to A, the reef front at transect H is high and large algal ridge. *Melobesia,* with *Porolithon onkodes* are dominant giving a pink or yellow - green colour at the reef front. In the case of transect A (low reef front without algal crest) coral cover is more than 70 % with *Pocillopora, Montipora, Millepora* and *Acropora.*

For all other transects (B to H) the algal crest has no coral except in some protected pools and crevices and only certain gastropods can settle : Patellidae *(Patella flexuosa)* and Turbinidae *(Turbo setosus).* The inner part of the algal crest is inhabited by Muricidae *(Drupa ricinus, Drupa clathrata, Drupa morum, Drupella fenestrata, Morula granulata* and *Thais aculeatus*). The density of these gastropods is from 1 to 12 / m^2. The most abundant species follow with mention of their maximum densities / m^2 : *Drupa ricinus* (10), *Morula granulata* (3) and *Turbo setosus* (2) at transect F according to prospected quadrats of 6 m^2. Presence and quantitative distribution of these species is in agreement with prospections on Fangataufa (Salvat, 1970).

<u>A fossil algal</u> crest or remnants of such a crest lie a few tens of metres behind the present algal crest on most of the transects. This fossil crest appears in the form of domes which are smooth on the surface ; they are eroded as usual by boring and scraping organisms and by mechanical action. Large plates of the crest are dislocated and thrown up on to the beach by waves during stormy weather. On transect B two samples of the fossil algal crest were dated : 2235 $\pm$ 80 B.P. and 3475 $\pm$ 100 years B.P. A similar fossil algal crest has been recorded both in the Tuamotu (Mururoa, Chevalier et al., 1968) and in the Cook islands (Woodroffe et al., 1990).

<u>The reef flat</u> without any remnants in elevation or depression is completely exposed at low tide. It is only partly exposed at high tide when the weather is calm. The reef flats are without organisms except boring algae of the genus *Entophysalis* giving its brown color to the carbonate substrate of the reef flat. On the inner part of the reef flat at transects C

and D, remnants of organisms were collected for dating : Serpulidae calcareous tube, 2115 ± 90 years B.P., and coral in growth position : 2410 ± 100 years B.P. These ages attest a higher sea level more than 2000 years ago when these organisms were alive.

Some megablocks occurs on the reef flat at different distances from the reef front where they have been torn out by cyclones. These blocs are not very big and not so numerous as they are in front of the hoa (between transect A and B) and around the western edge of the atoll (between transet A and K).

Conglomerate and remnants of conglomerate are present in some places. These horizontal flagstones stand 0.70 to 1.50 m higher than the reef flat. Old coral conglomerates were investigated in many other French polynesian atolls. Close petrological inspection of thin sections of rocks has shown that there is a consistent difference between the lower and the upper part. The lower had a cementation occurring in the marine phreatic zone when the upper was in the marine vadose zone. The limit between the two zones is correlated with the mean low tide of a previous sea level. Tens of datings on conglomerates of many Tuamotu atolls gave an age of 2000 - 3000 years B.P. related to a sea level 0,9 - 1,0 m higher than today from 5000 to 1500 years B.P. (Pirazzoli and al., 1985 and 1988). The same results were observed in the Cook Islands (Woodroffe et al., 1990) but with differing relative sea-level falls according to the island considered. A *Porites* cemented on the conglomerate was dated at 2140 ± 180 years B.P. Gastropods Littorinidae are the only ones living on the conglomerate : *Tectarius grandinatus* and *Littorina coccinea* whose densities are very low comparatively to those observed in Fangataufa. A third species, *Nerita plicata*, is unusual on the external reefs on Nukutipipi.

Beach rocks are present on transects A, B and C, on the northern part of the atoll. They attest the previous existence of motu or sand accumulation which has been removed.

From these observations and datings, the following conclusions point out the main features of the reefs back to motu :

1 - the reef flats of Nukutipipi are entirely exposed at low tide and without benthic organisms except boring algae *(Entophysalis)*. This is an originality of Nukutipipi not yet reported either on Rangiroa (Stoddart, 1969) nor in Mururoa (Chevalier et al., 1968)

2 - a fossil algal crest, remnants of organic skeletons on the reef flat, and old conglomerate have been dated. They attest a previous sea level higher than the present one, at a time 3500 to 2000 years B.P. This is in agreement with research results on other Tuamotu atolls.

3. There is no "feo" on Nukutipipi as they exist on Rangiroa (Stoddart, 1969) or other Tuamotu atolls : Anaa (Newell, 1956 and Pirazzoli and al. 1985) and Kaukura (Ranson, 1962). We know that these remnants of post inter-glacial reefs are only distributed on atolls in an arc as a result of flexing of the lithosphere beneath the load of Tahiti Moorea.

SUBMERGED REEF :

From the north-west to the south-east the atoll rim is linear. From transect K to I (figure 8) the ocean waves breaking on the reef front spread over the submerged reef at both low and high tide. The situation of this reef is very different to the previous ones (islet reefs) as it is submerged all the time by at least 0,50 m water.

This submerged reef is in two parts. The first is equivalent to the reef flat and the second to a lagoon sand platform. They are separated by a line of scattered remnants of old conglomerate, lying between the south parts of the two motu. These remnants, 30 to 40 cm above low tide level, are actively eroded. A sample was dated at 4375 ± 95 years B.P. The reef front is a very high algal crest due to the important hydrodynamic action of the south swell. Calcareous red algae have their maximum development with construction up to 2.5 m above low tide level. This situation at Nukutipipi is the same as at Mururoa (Chevalier et al., 1968), at Gambier (Brousse et al., 1974) or on northern atolls such as Rangiroa (Stoddart, 1969) or Takapoto (Chevalier et al., 1979). In this high-energy environment some molluscs

and echinoderms settle. Among the first are polyplacophore *(Chiton sulcatus)* and gastropods *(Patella flexuosa, Turbo setosus* and *Drupa ricinus)* and an Opisthobranch Atyidae, *Smaragdinella calyculata,* with a very large foot. Among the second are echinoids *Heterocentrotus mammillatus* and *Colobocentrotus pedifer.* The fauna is more diverse along and just behing the creviced inner edge of the algal crest with scleractinians *(Porites, Pocillopora, Acropora, Millepora),* green algae *(Caulerpa urvilliana, Codium sp.),* zoantharia *(Scleroderma),* holothurians *(Actinopyga mauritiana)* and molluscs *(Drupa ricinus, Morula uva, M. granulata, Dendropoma maxima).* An edge with more than 50 % coverage of *Porites, Millepora, Pocillopora* and *Acropora* leads to the reef flat. Some very scattered remnants, 1 m above the low tide level, can be observed some ten metres behind the inner edge of the algal crest. A sample, boundstone with foraminifera and calcareous algae, appeared to be a remnant of a fossil algal crest and was dated at 3560 ± 110 years B.P.

The submerged reef flat is a smooth surface covered by a very thin algal mat (some millimeters) holding fine sediments. From place to place some scleractiniains are present but coral coverage is less than 1 % : *Pocillopora verrucosa, Acropora sp.,Montipora danae, Pavona varians, Coscinaraea columna, Fungia sp., Porites lichen* and *Leptastrea purpurea* . Benthic organisms on this reef flat are only echinoderms and molluscs : *Holothuria atra* whose abundance increases towards the inner part of the reef flat but never more than 0,2 individuals / m^2 - gastropods with dominance of Conidae *(Conus ebraeus, C. sponsalis, C .miliaris, C. chaldeus, C. nanus, C. flavidus)* most of them being worm feeding, along with some other species : *Drupa speciosa, D. grossularia, Morula uva, Cypraea moneta* and *Cerithium citrinoides*

From the geomorphological point of view the submerged reef of the south rim is also a special feature not previously mentioned in other atolls. It consists of a reef flat, some remnants of old conglomerate and a sand lagoon platform, all in continuity with a constant inflow of ocean waters. Such a unit has not been reported either from Rangiroa (Stoddart, 1967) nor from Mururoa (Chevalier et al. 1969) and from all other atolls surveyed since these observations.

HOA AND MEGABLOCKS :

The channel, on the north rim of the atoll, between the two motu, is a communication between the ocean and the lagoon. Most of the time, unless there are strong northerly winds or and cyclones, water flows from the lagoon to the ocean. The hoa is not deeper than 1 m. In its inner (lagoon side) and central parts it is a smooth flagstone as on the submerged reef flat. Its outer part near the ocean is depressed comparative to the reef flat facing the islets and the coral coverage is from 10 to 50 % with dominance of *Pocillopora, Porites, Acropora, Montipora* and *Millepora.* Many megablocks are scattered over this outer part of the hoa and on its edges. Some are more than 25 m^3. They have been placed on the reef flat by cyclonic events as in many Tuamotu atolls (Bourrouilh-Le-Jan et Talandier, 1985). Most of them are grey in colour being incrusted with *Entophysalis* (boring algae) but some are white having recently been positioned by the two cyclones at 1983. These blocks were part of the present reef front where the waves break and have been torn out from the reef front facing the hoa. An aerial view of this edge clearly shows deep indentations on this reef front.

LAGOON AND COMMUNITIES

The lagoon is bordered by the motu, by the hoa or by the linear remnants of old conglomerate on the submerged rim. Facing the motu the limitation of the lagoon is the intertidal zone which is either narrow with coarse material or large with large beaches of white sand . Such beaches occur when there is a large sand platform before the lagoon slope. The inner part of the hoa is sand banks - 2 to 4 metres deep - between the lagoon slope and the flagstone of hoa - less than 1 m deep. The limit of the lagoon on the linear submerged reef is marked by the scattered remnants of old conglomerate. Entering the lagoon from this point one can observe, a sand platform of no less than 400 metres before the lagoon slope. Such a delimitation of the lagoon gives a total surface of about 2,20 km^2 for a total atoll of 5,64 km^2. As mentioned in the introduction, half this surface (about 110 hectares) is shallow sand substrate (less than 2 m deep) the other is the deep lagoon with a mean depth 15 m and without patch reefs reaching the surface.

HYDROLOGY AND HYDRODYNAMISM :

Ocean waters entering the lagoon over the submerged reef flow out by the hoa. Such is the regular circulation of the sea water, except when very strong winds and/or swell occur from the north or in the case of catastrophic events such as hurricanes . The tide is about 40 cm, but the level of the water in the lagoon is more related to sea conditions (more or less swell, and its direction) and to wind conditions. In quiet atmospheric and oceanographic conditions we observed in a 25 cm difference between low and high tide during springs. However, with a strong southerly swell we observed a 44 cm amplitude. Taking into consideration a total lagoon surface of 2,20 km^2, the volume of water due to a 25 cm amplitude is 550,000 m^3 and 880,000 m^3 for a 40 cm amplitude.

Oceanic water entering the lagoon is between 23°C and 27.5°C during the year (reference to Mururoa in the vicinity of Nukutipipi), with maximum temperature from February to April and minimum in September-October. Year-round salinity is 36 ‰. Nutrient concentrations are very low, which is a common feature for oceanic waters in French Polynesia. According to Renon (1989) nutrients in oceanic waters are the following in µ at g/l = NO_2 : 0,1 ; NO_3 : 0,1 ; PO_4 : 0,4-0,6 ; Si $(OH)_4$: 1,5.

In calm weather, lagoon water temperature can rise to 30°C (25 to 30°C) on the sand platform near the beach, and up to 29.5°C (25 to 29.5°C) on the sand platform after the submerged reef flat, and up to 26.5°C (26 to 26.5°C) on the lagoon floor. These temperature variations were recorded over a few days in November 1988. Salinity variations due to rainfall were observed in shallow water on the lagoon platform near beaches (less than 2 ‰). Nutrient concentrations in the lagoon were identical to those in the ocean. A secchi disc (30 cm diameter) disappears at a depth of more than 25 m in the ocean, but becomes invisible at 7 or 10 m in the lagoon.

SAND LAGOON PLATFORM :

More than half the total surface of the lagoon has a sand substrate without any patch coral reef. Maximally 2 metres deep these sands are medium to fine, with a mean diameter between 400 to 600 microns and with a fraction of coarse elements, mainly lamellibranch shells. Nine stations were surveyed (Figure 7) on November 1988. At each station dead Cardiidae shells of the local and common cockle in Tuamotu lagoons (Richard, 1982 a), *Corculum fragum (Cardium fragum),* are abundant both within and on the surface of

the sediment . Such was not the case during the preliminary survey of the lagoon in 1982 at which time a very important alive population of the cockle covered these shallow white sand flats. The disastrous cyclones in 1983 completely removed the substrate and entirely destroyed the population of *Corculum fragum* which , five years after the event has not yet recovered. We were unable to find even a young population of the cockle. Some *Holothuria atra*, another very common inhabitant of shallow sand flats in Tuamotu atolls, are present but very scare (a few individuals per hectare) as opposed to important concentrations in other atolls (Salvat, 1975). With the exception of two molluscs (*Vexillum cadaverosum* - gastropod Costellariidae - and *Codakia divergens*, lamellibranch Lucinidae), the only macro invetebrate living in these sands is an Enteropneust (acorn-worm) ot the genus *Balanoglossus*. Their density was between 16 and 124/m^2, with a mean value of 12/m^2.

DOME PATCH REEFS LAGOON :

As mentioned in the introduction, the central lagoon has no patch reef emerging from or near the surface. From the air, the lagoon - bordered by green shallow waters - appears entirely blue. However, a multitude of small submerged patch reefs can be seen very close to one another from a plane flying over the lagoon and on the aerial photograph we had. A bathymetric survey has been undertaken with a sounder along 5 lines, 3 of which are indicated in Figure 8. The mean depth of the lagoon is between 12 and 15 m with some zones or points going down to 17-18 m. Many indentations on the profile of the sounder recording are no more than 2 to 4 m high from the bottom but some are higher with a maximum of 6 m. Observation of the aerial view covering the entire lagoon leads to the conclusion that the bottom of the lagoon is 85-90 % sand and 10-15 % patch reefs. This percentage of hard substrate is very high compared to other closed or open Tuamotu atolls where sand substrate is always more than 95 %.

Patch reefs in the lagoon are in the form of a hill or a dome as observed during more than fifteen dives which enabled us to characterise these coral hills : ten to fifteen metres in diameter, 2 to 4 metres high, round at the base, sometimes with a massive coral construction at or near the summit but always consisting only of dead branches of *Acropora*. This was the first time we have seen such a lagoon patch reef morphology which we will call a "dome patch reef" with the characteristic of being so numerous and widespead in the lagoon. An estimate of the number is about 2 500 for the 110 hectares of the deep lagoon.

Dead branches of the *Acropora* branched form species are tangled on the entire thickness of the dome patch reef in a cavernous structure. This is the case of all the patches indicated on figure 9 with their geomorphological characteristics shown in table C. When present, coral at the summit of the dome patch reefs is as dead as *Acropora* on the slopes. Dome patch reefs with surfaces, of 100 to 225 m^2 (diameter from 8 to 12 m), have only a few square decimeters of living scleractinians. Information on these scleractinian species and their very low coverage on the lagoon dome patch reefs is given in table C. At the time of the prospections there were no living branched scleractinians. Two species are more abundant than others : *Leptastrea transversa* (7/10 patches) and *Psammocora contigua* (4/10). We noted only dead *Acropora* without a living population, very poor diversity , very poor coral coverage of other species and spatial homogeneity in the entire lagoon.

Along with filamentous green algae and Cyanophyceae algae, *Caulerpa* and *Microdictyon* Chlorophyceae abundant on the dome patch reefs. Presences, absences and abundances are mentioned in table C. We note that some patches have no important algal coverage (n°2, 4, 5, 9 and 12) while others are dominantly covered (n°1, 10, 11, 13 and 14).

Patch reef numbers 1 and 11 are 100 % covered by the two algae : C. *racemosa* at the base and *C. racemosa* and *C. urvilliana* mixed on the slopes. Patch reef numbers 10, 13 and 14 are entirely covered by *C. urvilliana*. Spatial homogeneity of algae population in the lagoon is the same as for scleractinians.

Molluscs are found on the dead *Acropora* branches with a dominant species, the Bivalve Chamidae , *Chama asperella*, and some other Bivalves with low densities (some scattered individuals) : *Chama iostoma, Pinctada maculata* (Malleidae), *Arca ventricosa* and *A. imbricata* (Arcidae) , *Isognomom sp.* (Isognomonidae), *Lithophaga cinnamonina* and *L. teres* (Mytilidae). We found some rare dead shells of the clam, *Tridacna maxima (Tridacnidae*), but no living specimen. Some old valves of *Pinctada margaritifera* have been found, given evidence of a past population of this species in the lagoon being to be completely eliminated some two decades ago by divers. Some thousands of *P. margaritifera* have been reintroduced during the last decade by the past owner of the atoll, M. Madec, and were alive on some patch reefs at the time of our prospection (1988).

Echinoderms are completely absent from this community which is surprising considering the echinoids and the abundance of algae on which they feed. One exception was one specimen of *Culcita novaeguineae* on patch reef number 5, a stellerid usualy feeding on corals ; the scleractinians cover on this patch reef was no more than 2 m^2 (^{1}/100 of the dome patch reef surface).

Crustaceans are discrete but the following species were collected of the Decapod family : *Platypodia granulosa, Chlorodiella nigra* and *Thalamita integra.*

Sponges are not abundant but encrusting forms have been collected and identified : *Chondrosia* and *Spiratrella* (cff *decumbens*). It was the same for Ascidians Didemnidae : *Lissoclinum fragile.*

As being unusual on coral reef communities throughout French Polynesia, one can mention the presence and abundance, on the iron platform for pearl oyster farming *(P. margaritifera*) near station 11 (figure 9), of a Deusterostomian Hemichordate Pterobranch *Cephalodiscus* sub genus *Orthoecus* . Their calcareous tubes, tiny and crumbly, constitute large tufts of many dcm3.

SAND BOTTOM LAGOON :

The sand substrate of the deep lagoon has been surveyed near each dome patch reef as reported on figure 9 and table C, with the exception of numbers 10 and 14. Three main aspects of the bottom were observed : a) bare sand with or without relief according to animal activity, b) sand with scattered *Cyanophyceae* in a large carpet or in round colonies, c) sand covered with a thick cover of green filamentous *Enteromorpha.*

Mollusc fauna is not diverse and all the species collected are mentioned in table D : 5 Bivalves and 3 Gastropods. Two of these were only recorded in the thanatocenose : *Tellina dispar* and *Pitar prora*. The most common one is *Lioconcha phillipinarum* , either living or dead at every station. All three Gastropods are alive when present at different stations. Quantitative survey give the following results for the three dominant species, *L. phillipinarum, Cerithium salebrosum* and *Arcopagia robust*ta with extreme densities, mean and standard deviation : 0-16 / 5,4 / 5,9 - 0-17 / 3,6 / 5,3 - 0-15 / 1,8 / 4,5 -.

No Actinians, nor Echinoderms were present on or in the sand substrate. Crustaceans Callianassidae were present but not identified. Sand Meiofauna showed a common composition with dominance of Nematods and of Harpacticoid Copepods and interstitial Polychete worms. Dead population of large foraminifera, *Marginopora (Soritidae)*, were very abundant in the sand and on its surface at some stations.

COMPARISON WITH OTHERS TUAMOTU LAGOONS :

Nukutipipi is the 77 th atoll of the 84 atolls throughout French Polynesia, from the largest (Rangiroa, 171 km^2) to the tiniest one (Tepoto Nord, 3,2 km^2) Absence of coral patch reefs reaching the surface in the lagoon have been underlined for Taiaro (Chevalier, 1976 - Salvat et al., 1977) and Scilly (Salvat, 1983). They are usually considered as remnants of karstic erosion after emergence during glacial periods but another explanation has been proposed in relation to the endo-upwelling theory (Rougerie et Wauthy, 1986) : rich nutrients raised by the thermal gradient inside the atoll substratrum emerged at some points on the lagoon bottom inducing prosperous coral growth in patch reefs. More than the absence of elevated patch reefs in Nukutipipi, as in Taiaro or Scilly, what is puzzeling to us are the hundreds of dead *Acropora* dome patch reefs. The state of conservation of *Acropora* branches means that mortality occured not many decades ago. If we understand that abiotic variability in such a tiny and enclosed lagoon (without a channel) is the explanation of mass mortality we don't have an hypothesis on the origin of these dome patch reefs. We plan to investigate the structure of some of these little dome patch reefs and date internal elements.

Flora and Fauna of the lagoon can be compared with other closed atolls of the Tuamotu archipelago. Each closed atoll has a poor diversity of flora and fauna compared to the open ones and qualitative and quatitative distribution of species of each of these lagoons are specific (Salvat, 1967). Very important dominance of some species has been well documented in many closed atolls for some benthic taxa : scleractinian corals, molluscs, echinoderms and algae : Reao (Salvat, 1971), Taiaro (Poli et Salvat, 1976), Mataiva (Delesalle et al., 1985), Takapoto (Richard, 1982b) and Scilly (Salvat, 1983). For each taxa the list of species living in these more or less confined environments is limited and one species can be present and dominant, in one lagoon and completely absent in another. We don't have at the moment a clear explanation of such a situation but we suspect that environmental parameters are not the main factor and that first dwellers in a new lagoon environment and species competition play a important role.

Algae (*Caulerpa* and *Microdictyon*) presents a high coverage in Nukutipipi lagoon which was not observed in other closed lagoons even when the species were present. We note also the complete absence in Nukutipipi of *Halimeda* which is mainly present in open lagoons.

Scleractinian corals *Acropora* and *Porites* are the most ubiquitous species, still living in almost all closed lagoons previously mentioned. In Taiaro *Porites* is the last surviving genus in the lagoon. The originality of Nukutipipi is the extreme dominance of *Acropora* whose branching form constitutes hundreds of dome patch reefs, and the fact that they are all dead without any new colonies.

Echinoderms are almost completely absent from Nukutipipi lagoon with the exception of some rare individuals of *Halodeima atra* which have such high populations elsewhere. The absence of echinoids is also very surprising.

Mollusc species of the hard substrate are few and with low densities. *Pinctada maculata,* a very common species of closed lagoons is there as well as *Chama asperella.*We note the complete absence of the clam, *Tridacna maxima.* Mollusc sand-dwellers are common species of closed lagoons but Nukutipipi is unusual in having totally dead populations of two bottom species (*Tellina dispar* and *Pitar prora*) and of one lagoon sand platform species (*Corculum fragrum*).

SUMMARY

The tiny atoll of Nukutipipi (5 km^2) was first surveyed in 1982, 1986 and mainly 1988. Uninhabited since its discovery by Carteret in 1767, the atoll was planted with coconut at the beginning of this century. It was seriously destroyed by Orama and Veena in 1983. The volcanic origin is estimated to be 16-17 million years old, since migration of the Pacific plate from the vicinity of the Pitcairn hot spot 1 500 km east-south-east.

If flora present a low diversity (21 species), the surviving *Pisonia* forest on the largest motu is most interesting. Land crustaceans, with large populations of hermit crabs (*Coenobita*) and reptiles, with parthenogenetic Gekkonidae, were identified. Ten species of birds, marine (8) and land (2), have been listed with hundreds of resident Red-tailed tropic birds (*Phaethon rubricauda*) as mentioned two centuries ago by Carteret. No mammal except *Rattus exulans* has been introduced to the atoll.

Reefs are described with some originalities : a) an entirely emerged reef flat on the north rim of the atoll, even at high tide, b) a fossil algal crest c) an uncommon submerged reef on the south rim.

The lagoon sand platform, less than 2 m deep, is a bare surface whose mollusc population of the common cockle, *Corculum fragrum,* was completely destroyed by hurricanes in 1983. It is characterised at the moment by a large population acorn worm (*Balanoglossus*). The deep lagoon, of 18 m maximum depth, without any patch reefs reaching the surface, is characterised by many hundreds of "dome patch reefs" exclusively constituted of dead *Acropora* coral branches. No more than 6 species of scleractinian corals present a living cover much less than 1 % on these patch reefs most of them covered by algae, *Caulerpa* and *Microdictyon.* Some gastropods have low density populations and there is no Echinoderm in the lagoon.

In the sediment 8 species of mollusc were identified, 2 of them exctinct and 1 alive as dominant (*Lioconcha*).

AKNOWLEDGEMENTS

We are grateful to colleagues who identified or confirmed identification of part of the collected material on Nukutipipi : J. Florence (ORSTOM, Papeete) for flora, J. Forest (Museum National d'Histoire Naturelle, Paris) for crustaceans, Y. Ineich (Museum National d'Histoire Naturelle, Paris) for reptiles, J.C. Thibault (Parc Naturel de Corse) for birds, G. Faure (University of Montpellier) for corals, C. Payri (Université Française du Pacifique) for algae, C. Levi (Museum National d'Histoire Naturelle, Paris) for sponges. J. L. Dhondt (Museum National d'Histoire Naturelle, Paris) for enteropneust. Our thanks also go to Mme Carr for assistance with our English.

LITERATURE CITED

BERTRAND M. et INEICH I., 1989. Répartition des Pterygosomatidae ectoparasites du Gecko *Gehyra oceanica* (Lesson, 1830) en Polynésie française. *Acarologia 28, 3 : pp. 241-250.*

BLANC C.P., et INEICH I., 1985. Statut taxonomique et distribution des Reptiles terrestres de Polynésie française. Note préliminaire. *C.R. Soc. Biogéogr., 61 (3) : pp. 91-99.*

BROUSSE R., CHEVALIER J.P., DENIZOT M., SALVAT B., 1974. Etude géomorphologique des îles Gambier. *Cah. Pacif., 18 (1) : pp. 9-119.*

BROUSSE R., 1985 . The age of the islands in the Pacific Ocean : volcanism and coral reef build up. *Proc. 5th Int. Coral Reef Symp., 6 : pp 389-400.*

CHEVALIER J. P., 1976. Madréporaires actuels et fossiles du lagon de Taiaro. *Cah. Pacif., 19 : pp. 253-264.*

CHEVALIER J.P., DENIZOT M., MOUGIN J. L., PLESSIS Y., SALVAT B., 1968. Etude géomorphologique et bionomique de l'atoll de Mururoa (Tuamotu). *Cah. Pacif., 12 : pp. 11-44.*

CHEVALIER J. P., DENIZOT M., RICARD M., SALVAT B., SOURNIA A., VASSEUR P., 1979. Géomorphologie de l'atoll de Takapoto. *J. Soc. Ocean. 35 (62) : pp. 9-15.*

DELESALLE B., et al., 1985. Environmental survey of Mataiva atoll, Tuamotu archipelago, French Polynesia. *Atoll Res. Bull., 286 : pp. 1-39.*

EMORY K.P., 1939. *Journ. Soc. des Océanistes.*

FLORENCE J., 1986. Flore et végétation. *Encyclopédie de la Polynésie française, Tahiti, 2, 2 : pp. 25-40.*

FOSBERG F. R., 1990. A review of the Natural History of the Marshall islands. *Atoll Res. Bull., 330 : pp. 1-100.*

HOLYOAK D. T. et THIBAULT J. C., 1984. Contribution à l'étude des oiseaux de Polynésie orientale. *Mem. Mus. Nat. Hist. Nat. (Paris), 127 : pp. 1-209.*

INEICH I., 1987. Recherches sur le peuplement et l'évolution des reptiles terrestres de Polynésie française. *Thèse de doctorat, USTL, Montpellier, le 10 novembre 1987 : 504 pages.*

INEICH I., 1989. Comparaison des herpétofaunes de Polynésie française et des Hawaii : l'Homme en tant que facteur biogéographique. *C.R. Soc. Biogéogr., 65, 1 : pp. 21-38.*
JOLINON J. C., 1988. La flore de l'atoll de Fangataufa. *Rapport Ronéoté, 88 pages.*
MONTAGGIONI L. F., PIRAZZOLI P.A., 1984. Utilisation des grès et conglomérats récifaux émergés en tant qu'indicateurs des variations récentes du niveau marin. *Coll. Lyon Trav. Mais. Orient., 8 : pp. 91-97*
OKAL E. A. et CAZENAVE A., 1985 : "A model for the plate tectonic evolution of the eastcentral Pacific based on Seasat investigations". *Earth and Planetary Science Letters 72 : pp. 99-116*
PIRAZZOLI P. A., MONTAGGIONI L. F., DELIBRIAS G., FAURE G., SALVAT B., 1985. Late holocene sealevel changes in the Society islands and in the Northwest Tuamotu atolls. *Proc. Fifth int. Coral Reef Cong., Tahiti,3 : pp. 131-136.*
PIRAZZOLI P. A., MONTAGGIONI L. F., SALVAT B. and FAURE G., 1988. Late Holocene sea level indicators from twelve atolls in the central and eastern Tuamotus (Pacific Ocean). *Coral Reefs 7 : pp. 57-68.*
POLI G. et SALVAT B., 1976. Etude bionomique d'un lagond'atoll totalement fermé : Taiaro. *Cah. Pacif., 19 : pp. 227-251.*
RENON J. P., 1989. Le zooplancton des milieux récifolagonaires de Polynésie. Variations temporelles, variations spatiales et bilan de production et d'échanges. *Thèse d'état, Université d'Orléans, 9 janvier 1989 : 359 pages.*
RICHARD G., 1970. Etude sur les mollusques récifaux des atolls de Reao et de Hereheretue (Tuamotu, Polynésie). Bionomie et évaluations quantitatives. *Diplôme EPHE, Paris, 6 Novembre 1970 : pp 1-102.*
RICHARD G., 1982 a. Bilan quantitatif et premières données de production de *Cardium fragum* (Mollusca, Bivalvia) dans le lagon de Anaa. *Malacologia, 22 (1/2) : pp. 347-352.*
RICHARD G., 1982 b. Mollusques lagunaires et récifaux de Polynésie française. Inventaire faunistique Bionomie Bilan quantitatif Croissance Production. *Thèse d'état, Université de Paris VI, 8 mars 1982 : 313 pages.*
ROUGERIE F., et WAUTHY B., 1986. Le concept d'endoupwelling dans le fonctionnement des atolls oasis. *Oceanologia acta, 9, 2 : pp. 133-148.*
SACHET M. H., 1983. Vegetation et flore de l'atoll de Scilly (Fenua Ura). *Jour. Soc. Océanistes, 77, 39 : pp. 29-34.*
SALVAT B., 1967. Importance de la faune malacologique dans les atolls polynésiens. *Cah. Pacif., 11 : pp. 7-49.*
SALVAT B., 1970. Etudes quantitatives (comptages et biomasses) sur les Mollusques récifaux de l'atoll de Fangataufa (Tuamotu Polynésie). *Cah. Pacif. , 14 : pp. 1-57.*
SALVAT B., 1971. La faune benthique du lagon de l'atoll de Reao (Tuamotu, Polynésie). *Cah. Pacif., 16 : pp. 30-109.*
SALVAT B., 1975. Qualitative and quantitative distribution of Halodeima atra (Echinodermata, Holothuridea) in the lagoons and reefs of French Polynesia. *Proc. 13th Pac. Sci. Congr. Vancouver, 1 : p.32*
SALVAT B., 1983. La faune benthique du lagon de l'atoll de Scilly, archipel de la Société. *J. Soc. Océan., 39 (77) : pp. 3-15.*
SALVAT B., CHEVALIER J. P., RICHARD G., POLI G., BAGNIS R., 1977. Geomorphology and biology of Taiaro atoll, Tuamotu Archipelago. *Proc. Third Int. Coral Reef Symp., Miami, 1 : pp. 289-296.*
SCOTT G. A. J. and ROTONDO G. M., 1982. A model for the development of types of atolls and volcanic islands on the Pacific lithospheric plate. *Atoll Research Bulletin, 260 : pp. 1-33.*
SPENCER T., 1989. Tectonic and Environmental Histories in the Pitcairn Group, Paleogene to Present : Reconstructions and Speculations. *Atoll Res. Bull., 322, pp. 1-21.*

STODDART D.R., 1969. Reconnaissance Geomorphology of Rangiroa Atoll, Tuamotu Archipelago. *Atoll Res. Bull., 125 : pp. 1-44.*

THIBAULT J. C., 1987. La faune terrestre et les oiseaux de l'atoll de Fangataufa. *Rapport ronéoté, 46 pages.*

THIBAULT J. C. et GUYOT I., 1988. Livre rouge des oiseaux menacés des régions françaises d'OutreMer. *Cons. Int. pour la Protection des Oiseaux, monographie n° 5 : 258 pages.*

WOODROFFE C.D., STODDART D.R., SPENCER T., SCOFFIN T.P., and TUDHOPE A.W., 1990. Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs , 9 : pp. 31-39.*

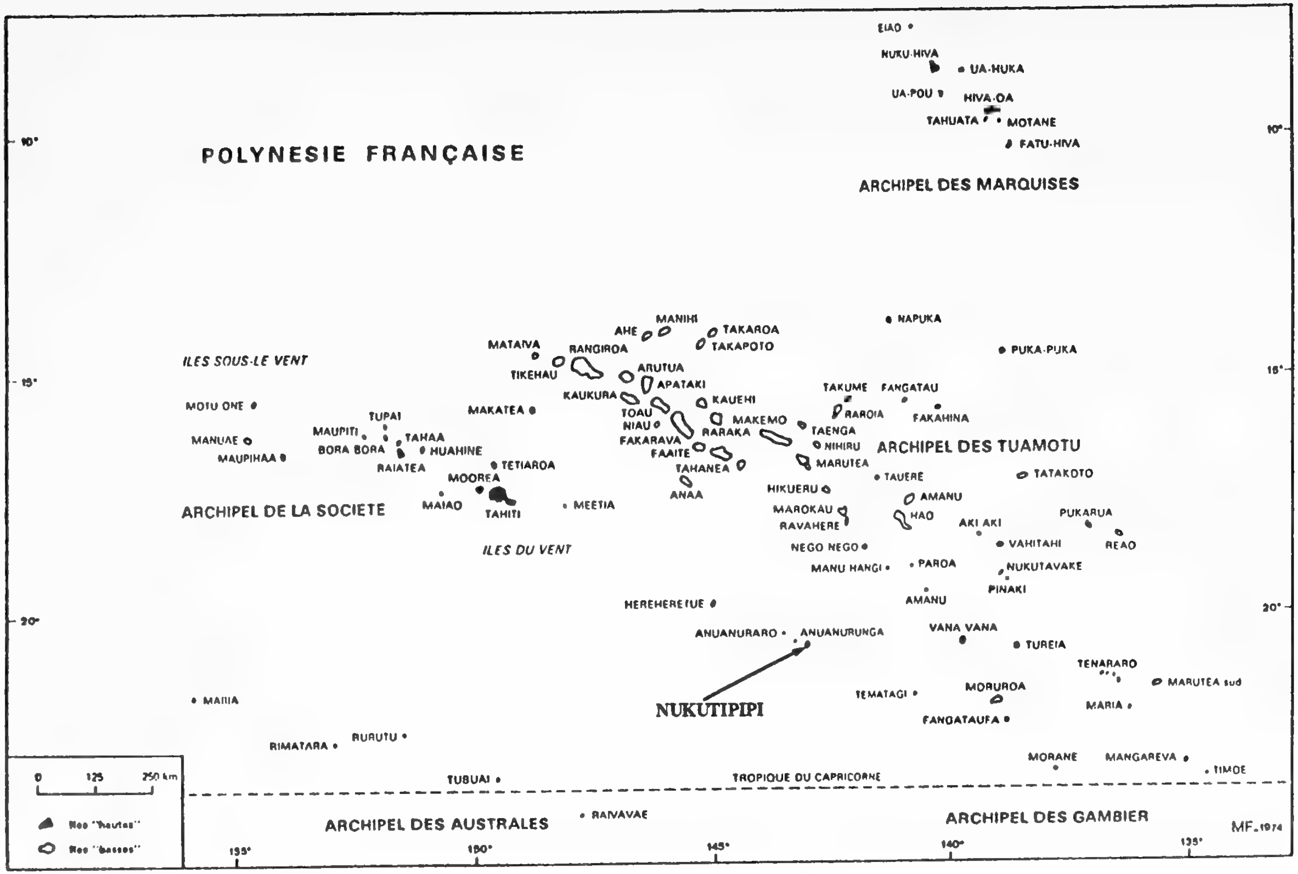


Figure 1 : French Polynesian archipelagoes . Localisation of Nukutipipi atoll in the Tuamotu archipelago.

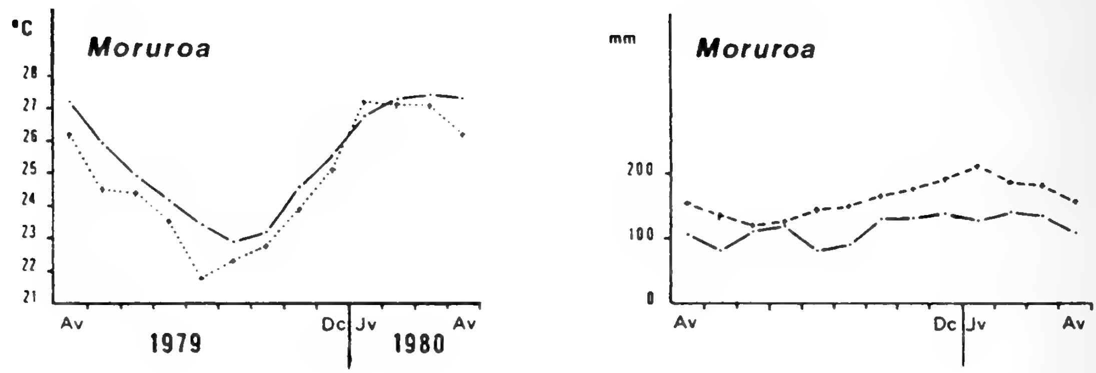


Figure 2 : Meteorological data on Mururoa, 430 km east of Nukutipipi and same latitude. Air (dashed line) and sea water (full line) temperature in C°. Precipitation (full line) and evaporation (dashed line) in millimeters. Mean monthly values over ten years (from RENON, 1989).

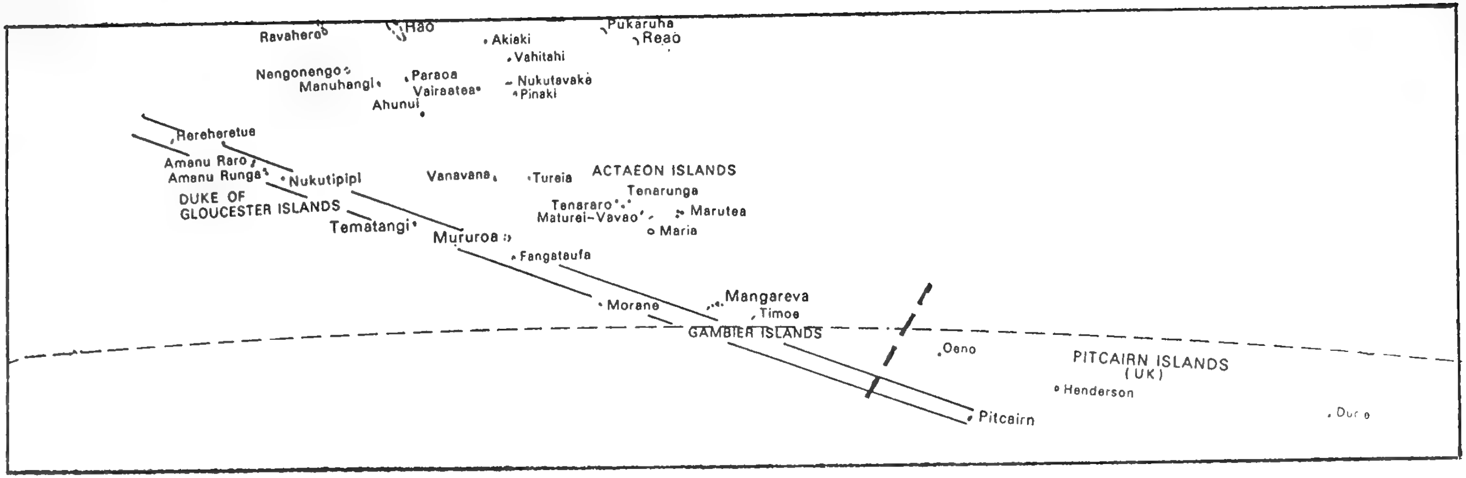
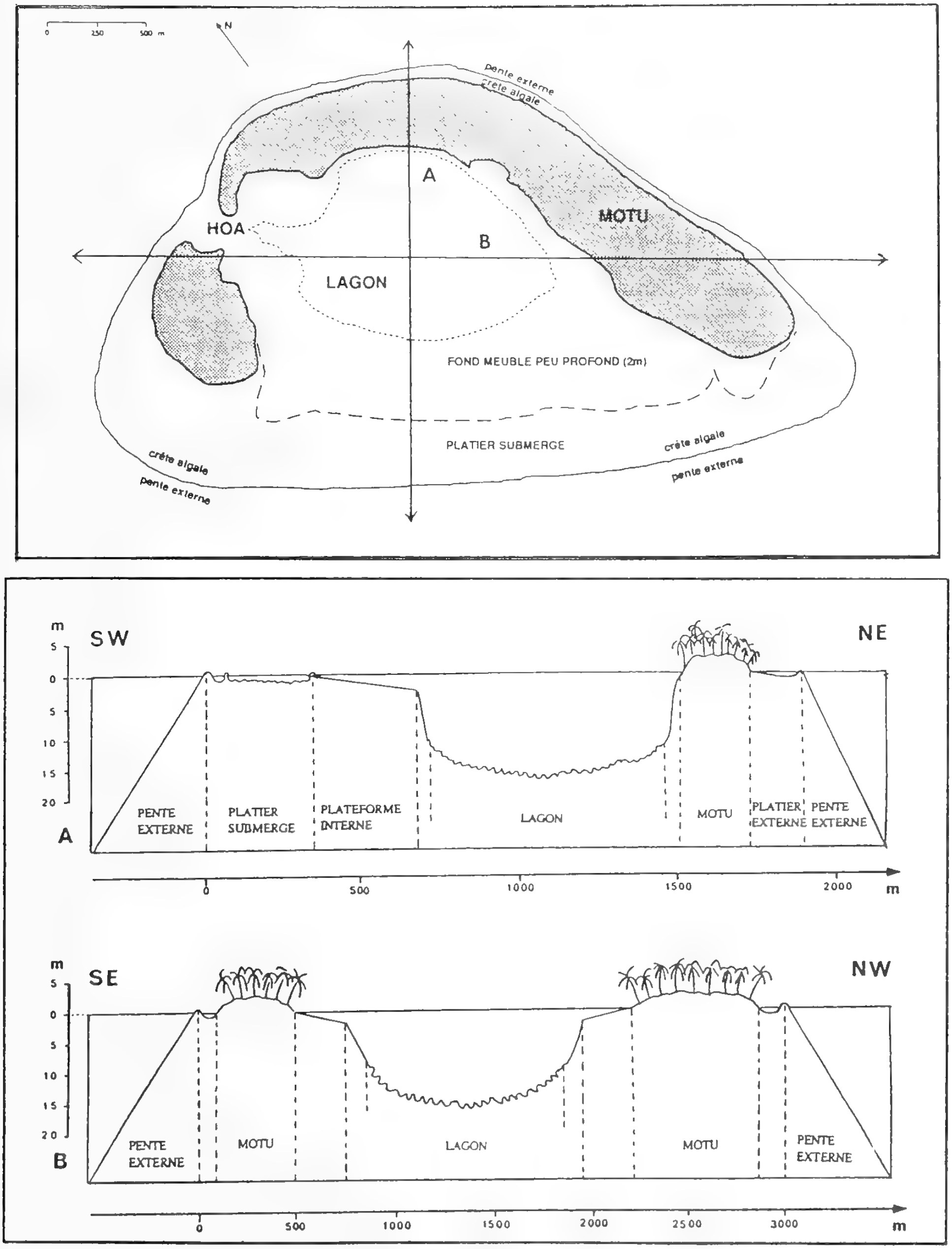


Figure 3 : Pitcairn -Hereheretue alignment from the hot spot near Pitcairn. Dashed line separates French Polynesia and United Kindom Islands.



Figrue 4 : Map of Nukutipipi atoll with two transects across the island and mention of the main geomorphological units.

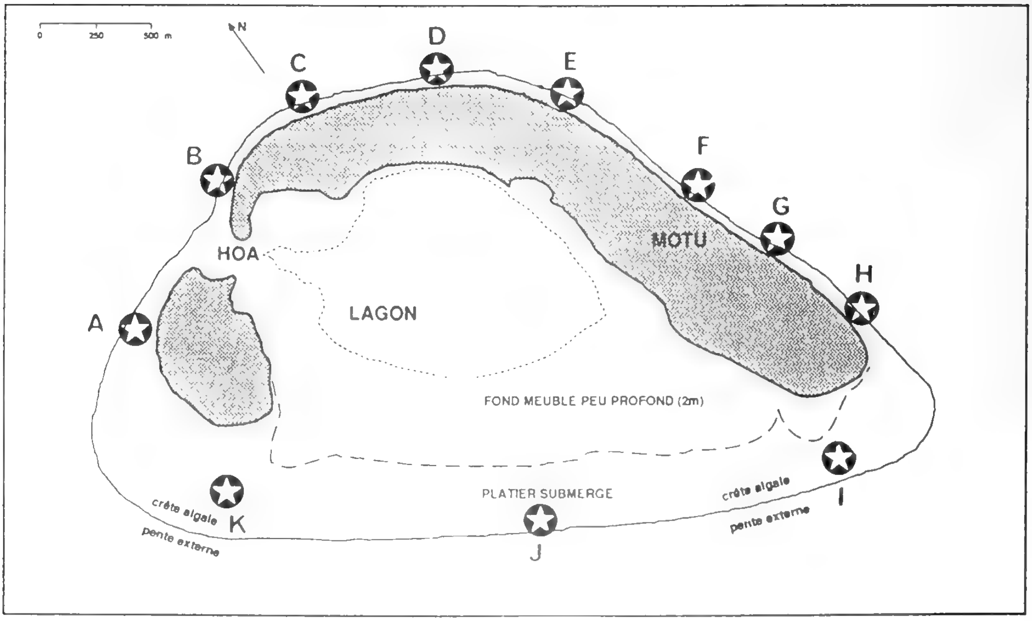


Figure 5 : Outer reef transects surveyed on Nukutipipi.

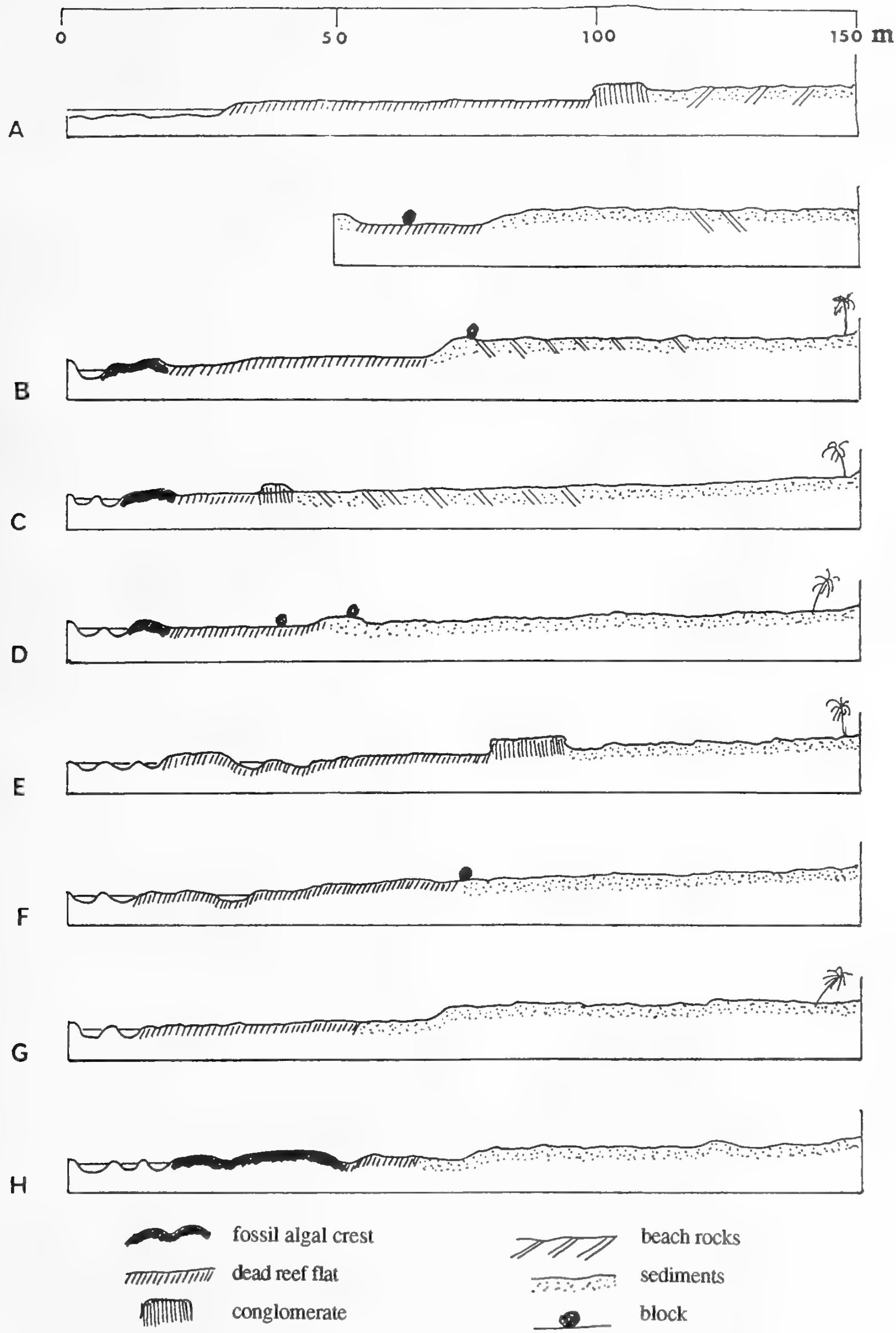


Figure 6 : Diagram of the morphology of the 8 transects prospected on the outer reefs of Nukutipipi. Letters (A to H) refer to the position of the transects on figure 5.

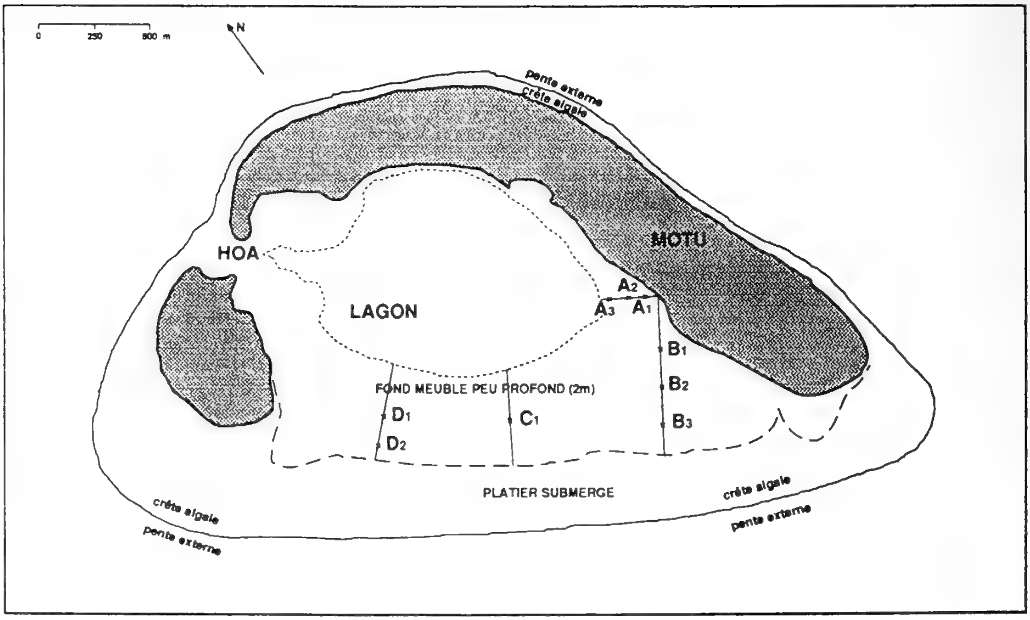


Figure 7 : Surveyed transects and stations on the sand lagoon platform .

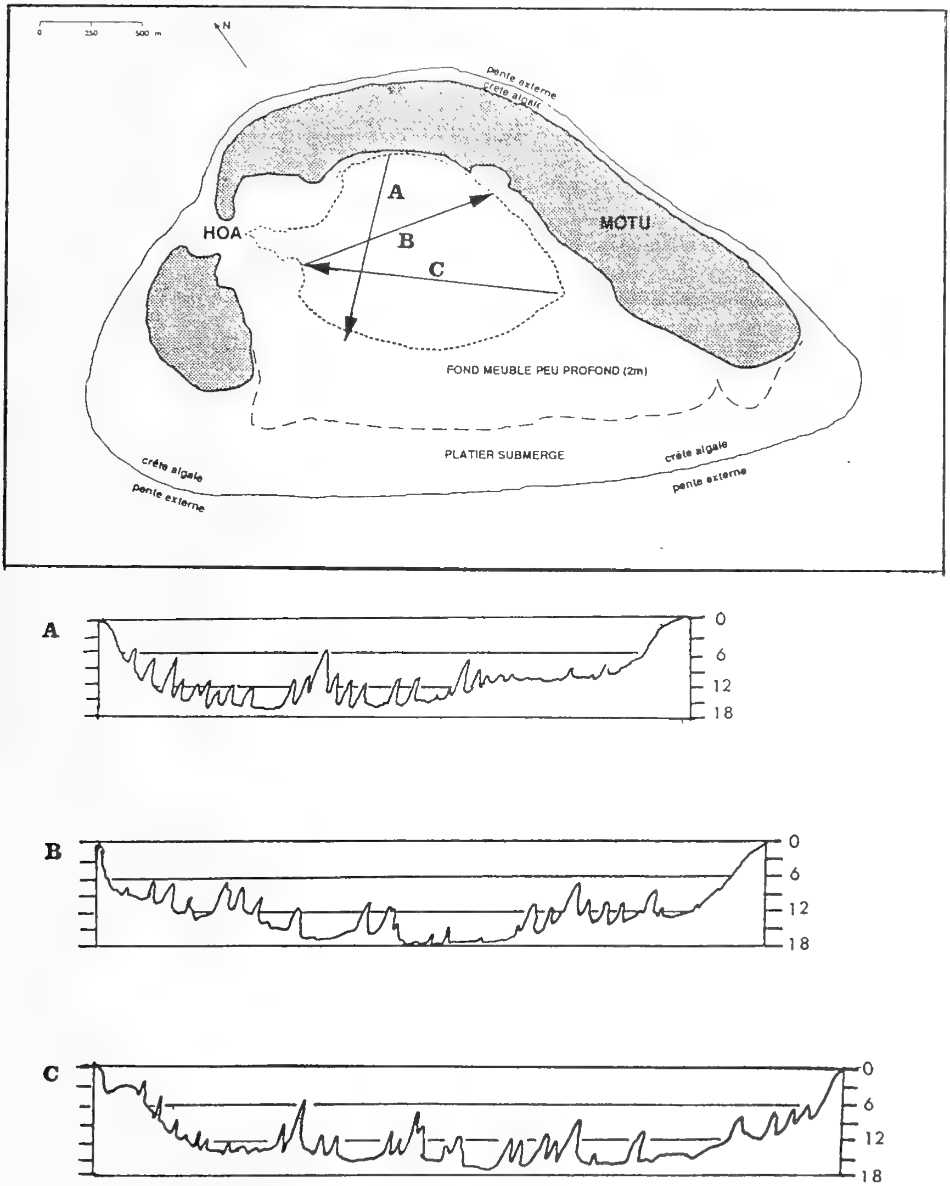


Figure 8 : Bathymetry along three transects in the lagoon.

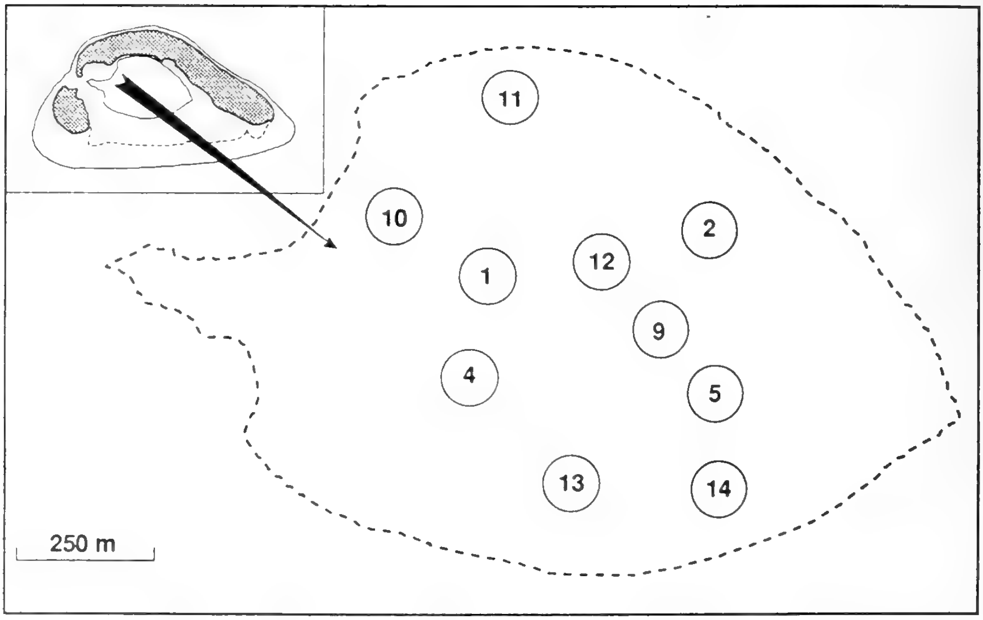


Figure 9 : Localisation of survey stations in the lagoon. Absent numbers correspond to planned but as yet not surveyed site.

- **Boraginaceae**
  Argusia argentea (L.f.) Heine
  Heliotropium anomalum Hook. & Arn.

- **Casuarinaceae**
  Casuarina equisetifolia L.

- **Cruciferae**
  Lepidium bidentatum Montin

- **Goodeniaceae**
  Scaevola taccada (Gaertn.) Roxb.

- **Gramineae**
  Lepturus repens (Forst.) R. Br.

- **Lauraceae**
  Cassytha filiformis L.

- **Lythraceae**
  Pemphis acidula Forst.

- **Malvaceae**
  Hibiscus tiliaceus L.

- **Moraceae**
  Artocarpus altilis (Park.) Fosb.

- **Musaceae**
  Musa troglodytarum L.

- **Nyctaginaceae**
  Boerhavia tetrandra Forst.
  Pisonia grandis R. Brown

- **Palmae**
  Cocos nucifera L.

- **Pandanaceae**
  Pandanus tectorius Soland.

- **Portulacaceae**
  Portulaca lutea Soland.

- **Rubiaceae**
  Gardenia taitensis DC.
  Guettarda speciosa L.
  Timonius polygama (Forst. f.) Rob.

- **Surianaceae**
  Suriana maritima L.

- **Tiliaceae**
  Triumfetta procumbens Forst.

- **Urticaceae**
  Laportea ruderalis (Forst. f.) Chew

Table A : Flora of Nukutipipi atoll (1988 observations)

- **Phaethontidae**
  Phaethon rubricauda Boddaert
- **Sulidae**
  Sula sula (L.)
- **Fregatidae**
  Fregata ariel (Gray)
- **Ardeidae**
  Egretta sacra Gmelin
- **Charadriidae**
  Numenius tahitiensis (Gmelin)
  Tringa incana (Gmelin)
- **Sternidae**
  Sterna fuscata L.
  Gygis alba (Sparrman)
  Anous tenuirostris (Temminck)
- **Muscicapidae**
  Acrocephalus (caffer) *ravus (*Wetmore)

Table B : Birds of Nukutipipi atoll (1988 observations)

FAMILLE	ESPECE										
	Numéro du paté	1	2	4	5	9	10	11	12	13	14
	Profondeur du plancher du lagon en m.	12	11	12	12	12	10,5	12	13	11	10
	Hauteur du paté en m.	2	2	2,5	3	3,5	1,5	2	2	1	1
	Diamètre du paté en m.	8	8,5	8	11	12	10	11	11	7	6
	Construction sommitale	oui	non	non	oui	oui	oui	oui	non	non	oui
	Flanc d'acropores cassés	oui	oui	oui	oui	oui	oui	oui	oui	oui	oui
SCLERACTINAIRES											
Thamnasteriidae	Psammocora contigua	P	A	0	0	P	0	P	0	0	0
Astrocœniidae	Stylocœniella guentheri	0	0	0	A	P	0	0	0	0	P
Pocilloporidae	Pocillopora damicornis	0	0	P	0	0	0	0	0	0	0
Poritidae	Porites cf. vaughani	P	0	0	0	0	0	0	0	0	0
Faviidae	Leptastrea transversa	P	P	P	A	P	0	P	P	0	0
	Cyphastrea serailia	P	0	0	0	0	A	0	0	0	0
ALGUES											
Chlorophyta	Caulerpa racemosa	PD	P	P	P	0	P	PD	PD	0	0
	Caulerpa urvilliana	PD	P	P	P	0	PD	PD	P	PD	PD
	Microdictyon okamurai	P	P	0	P	P	0	P	P	0	0

Table C : Dome patch reefs of the Nukutipipi lagoon. Distribution of scleractinian corals (P = present only by a few dcm^2, A = abundance between 0,5 and 1,5 m^2, 0 = absent) and of algae (P = present with a cover less of 5 % of the patch reef surface, PD = Dominant with a cover more than 30 %)

STATIONS DU LAGON	1	2	4	5	9	11	12	13
BIVALVES								
Lucinidae								
Codakia divergens		B			B			
Tellinidae								
Arcopagia robusta	T		B					
Tellina dispar	T	T			T			T
Veneridae								
Lioconcha philippinarum	T	B	B	T	B	B	T	B
Pitar prora				T				
GASTROPODES								
Cerithiidae								
Cerithium salebrosum	B	B	B	B	B	B	B	B
Rhinoclavis fasciata	B	B	B			B		B
Costellariidae								
Vexillum cadaverosum	B	B				B	B	

Table D : Distribution of molluscs in sand bottom lagoon stations. B = bios, living species - T = thanatocenose , dead specimens.

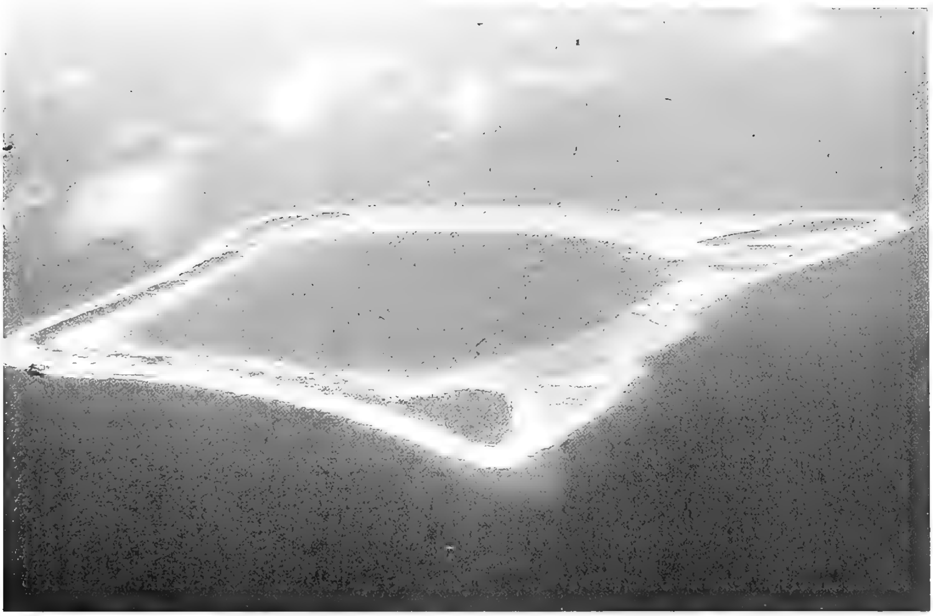


Plate 1 : Anu Anuraro Atoll, Duke of Gloucester islands, Tuamotu archipelago. (Ref . plate : 1988 / A-5).

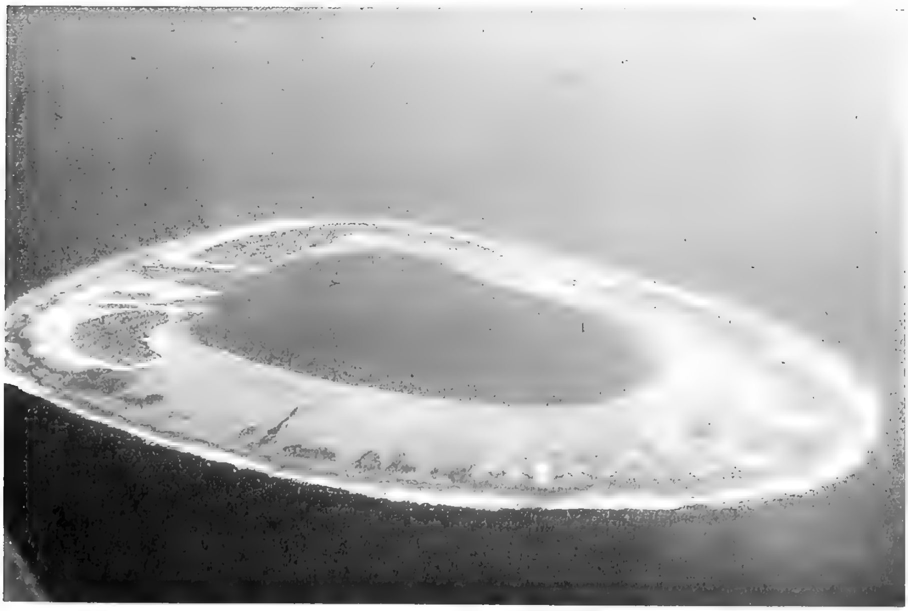


Plate 2 : Anu Anurunga Atoll, Duke of Gloucester islands, Tuamotu archipelago. (Ref. plate : 1982 / 9-24).

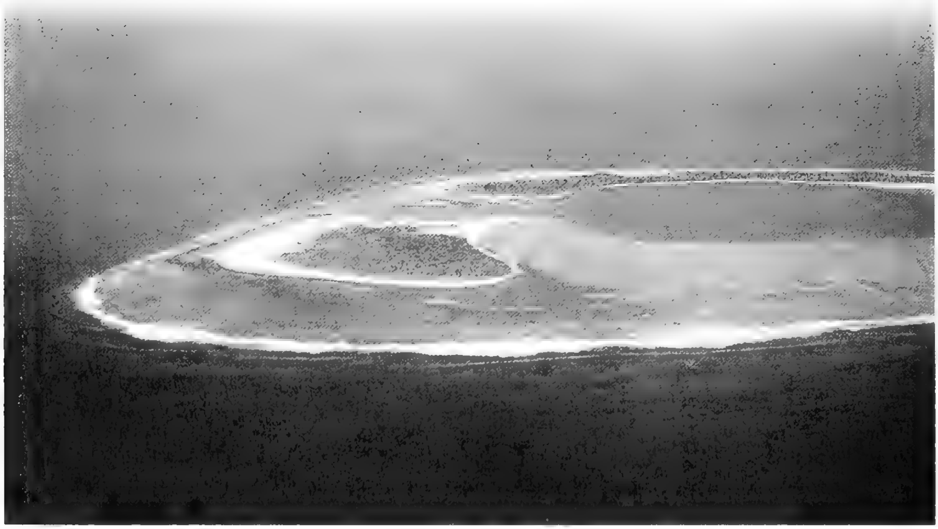


Plate 3 : Nukutipipi atoll, north-west part (from the south), Duke of Gloucester islands, Tuamotu archipelago (Ref. plate : 1982 / 9-17).

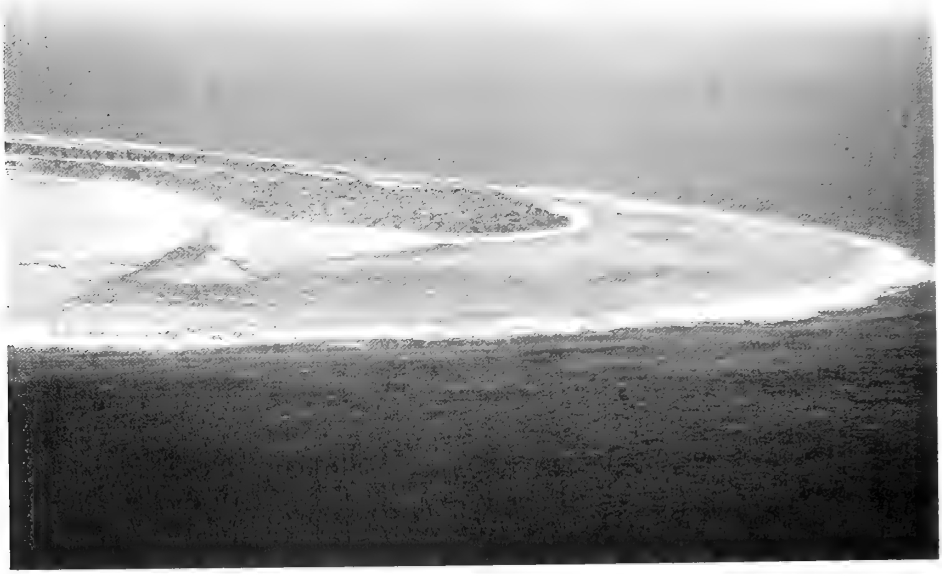


Plate 4 : Nukutipipi atoll, south-east part (from the south), Duke of Gloucester islands, Tuamotu archipelago (Ref. plate : 1982 / 9-10).

Plate 5 : Composition of the aerial cover prints of Nukutipipi atoll in 1965. Length (from reef fronts) is about 3,5 km. Surface is about 5 km^2. Little motu (lower left) and large motu (above).

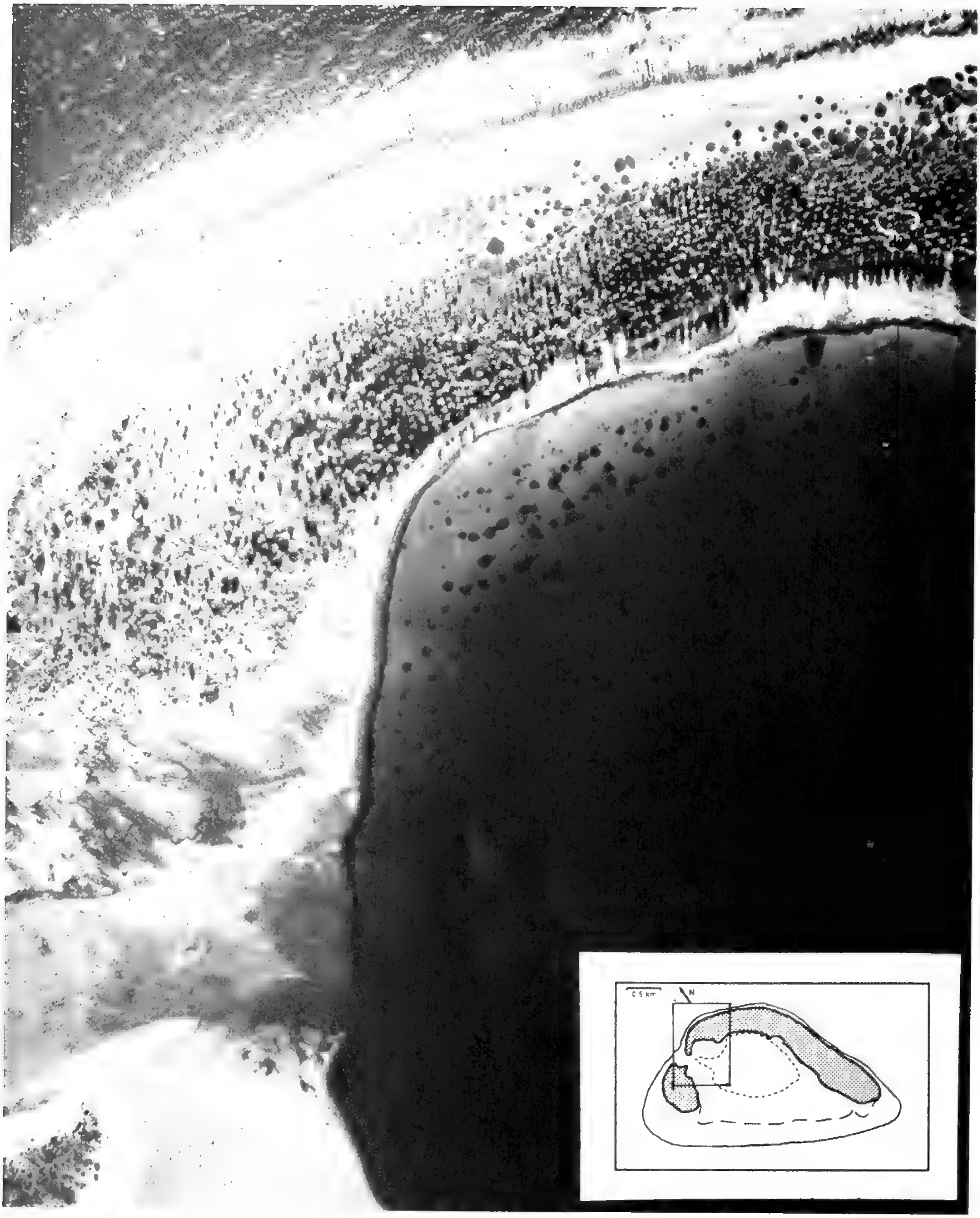


Plate 6 : Print of one aerial view of Nukutipi atoll on 11 th July 1965. Localisation indicated on the reference map. Northern parts of the large (background) and little (foreground) motu separated by the hoa where lagoon waters (right) exit to the ocean (left).

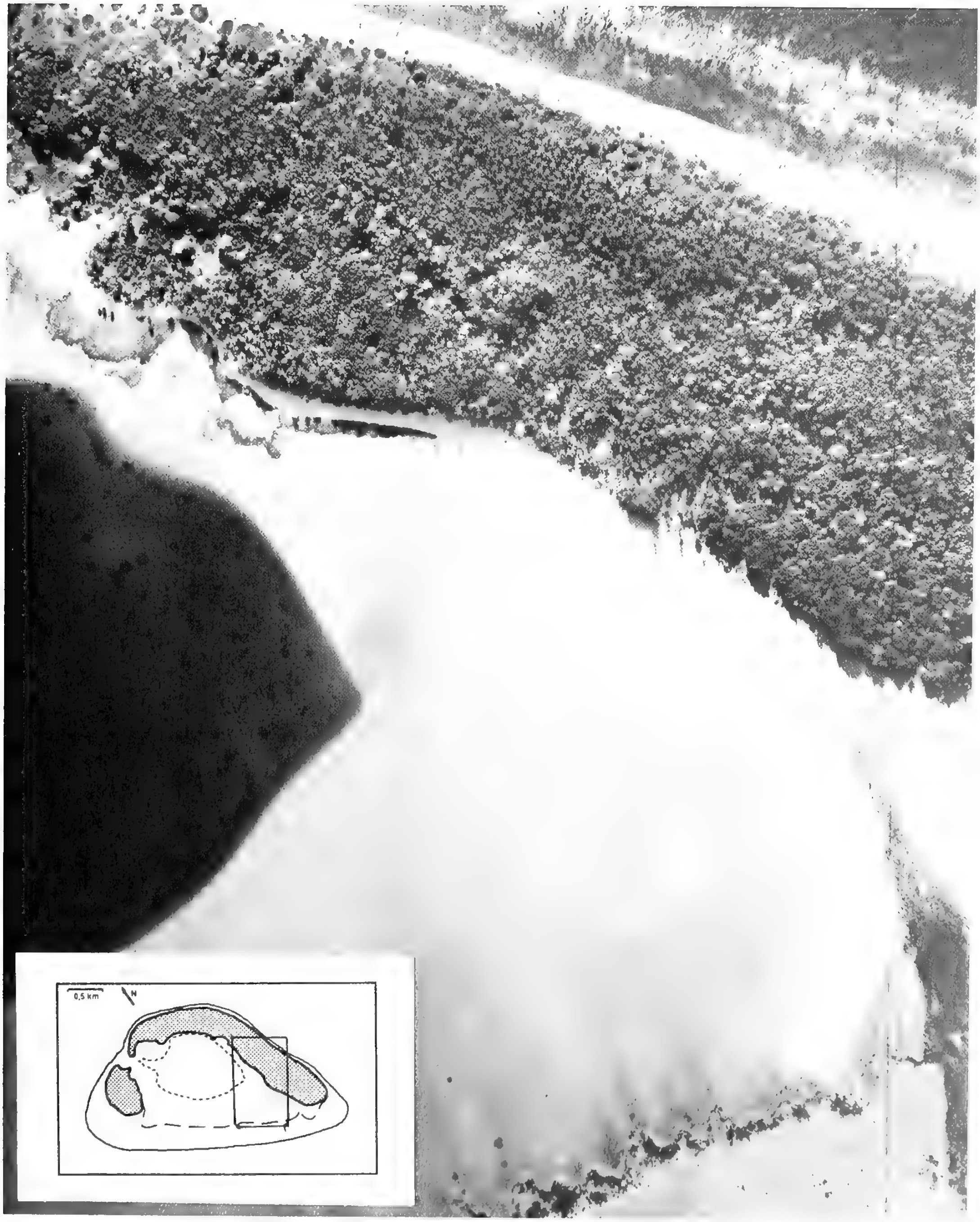


Plate 7 : Print of one aerial view of Nukutipi atoll on 11 th July 1965. Localisation indicated on the reference map. Up : Large motu - Down : sand lagoon platform (2 m deep) - Left : deep lagoon (15 m deep) with submerged dome patch reefs.

Plate 8 : Print of one aerial view of Nukutipi atoll on 11 th July 1965. Localisation indicated on the reference map. Southern part of large motu with primitive vegetation (*Pisonia grandis* forest), emerged reef flat of the south eastern part of the atoll, reef front and algal crest where waves from the ocean break.

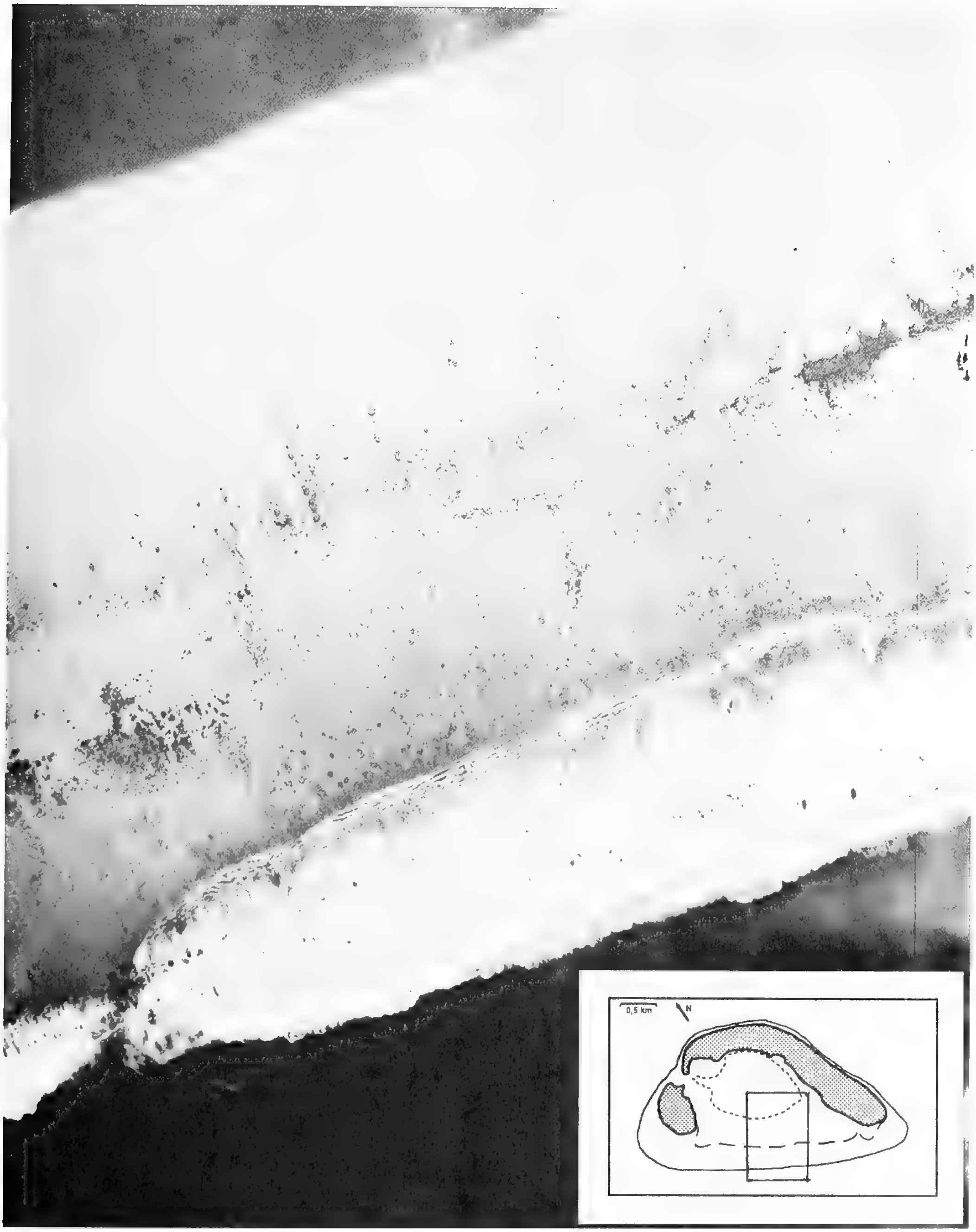


Plate 9 : Print of one aerial view of Nukutipi atoll on 11 th July 1965. Localisation indicated on the reference map. From top to bottom : deep lagoon with submerged patch reefs, sand lagoon platform, remnants of old conglomerate, submerged reef flat, algal crest with breaking waves from the ocean.

Plate 10 : Southern part of the large motu - *Pisonia* forest with *Pandanus*, *Guettarda* and *Cocos*. Airfield on the right background. (Ref. plate : 1986 / 8-11).

Plate 11 : Vegetation on the large motu : *Pisonia grandis* (right), *Cocos nucifera* (center) and *Pandanus tectorius* (left). (Ref. plate : 1982 / 7-27).

Plate 12 : Northern part of the large motu with coconut plantation (foreground) and the little motu (background) separated by the hoa ; 1982 before hurricanes. (Ref. plate : 1982 / 7-15).

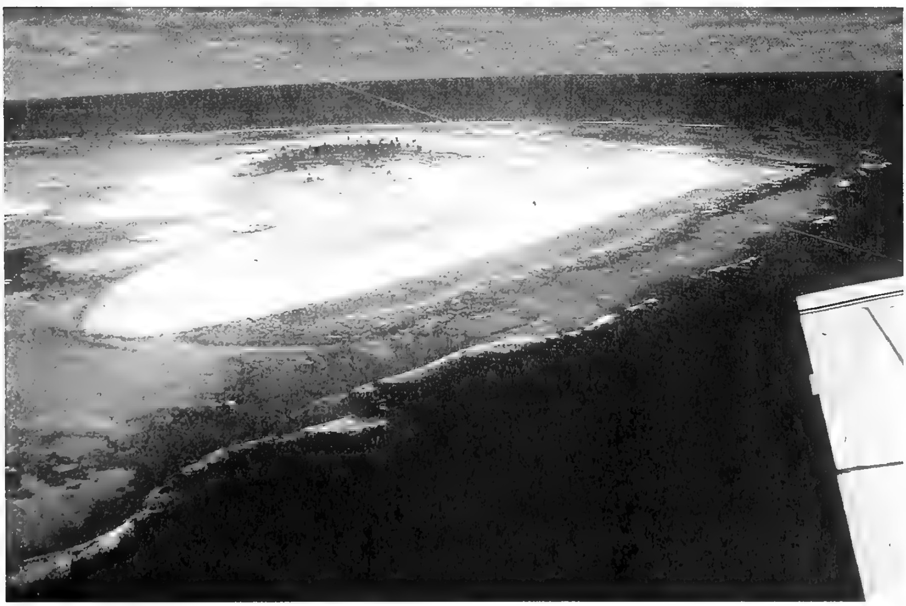


Plate 13 : The little motu in 1986 with vegetation reduced by 2/3 after hurricanes Orama and Veena in 1983 (Ref. plate : 1986 / 8-18).

Plate 14 : The Red-tailed tropic bird, *Phaethon rubricauda*, the most representative bird of Nukutipipi atoll. (Ref. plate : 1988 / 6-23).

PLate 15 : Hermit crab, *Coenobita perlatus*, here in a *Turbo setosus* shell, forms a large population on Nukutipipi atoll.

Plate 16 : Low algal crest of northern reef flat. A block torn up from the reef front to the reef flat during cyclone (Ref. plate : 1988 / 3-1).

Plate 17 : Completely emerged reef flat of northern part of the atoll. A fracture parallel to the reef front (Ref. plate : 1988 / 3-6).

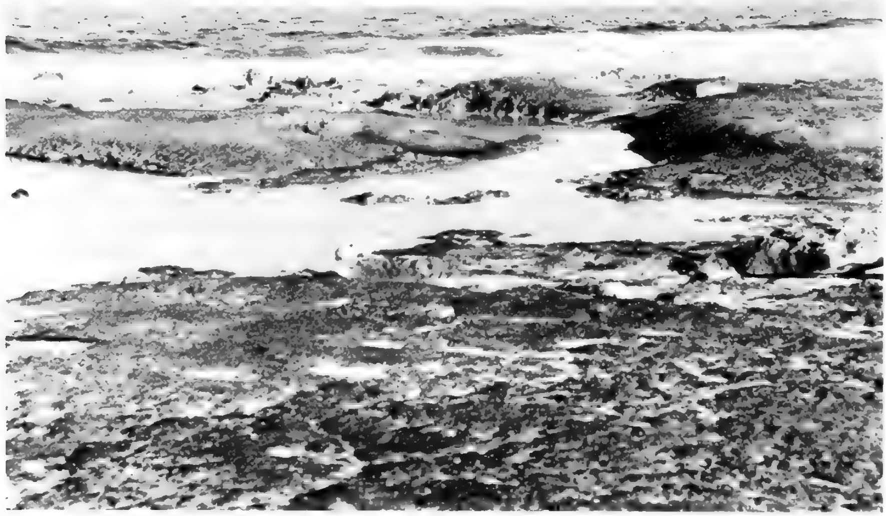


Plate 18 : Fossil algal crest as dome mounts (foreground) behind the present low one (background). Northern rim of the atoll (Ref. plate : 1988 / 6-32).

Plate 19: Fossil algal crest with dislocated plates which are thrown up by waves. Dated 2235 and 3475 years B.P. (Ref. plate : 1988 / 6-18).

Plate 20 : A megablock, 4 m high and about 30 m^3 torn up from the reef front to the reef flat during hurricane Orama or Veena, 1983 (Ref. plate : 1986 / 1-29).

Plate 21 : A megablock, 10 m long and about 25 m^3, torn up from the reef front (background) to the reef flat during hurricane Orama or Veena, 1983 (Ref. plate : 1986 / 1-25).

Plate 22 : Old conglomerate remnants of the south rim of Nukutipipi atoll, separating submerged reef flat (rigth) and sand platform lagoon (left). Dating gives 4395 ± 95 years B.P. Ref. plate : 1982 / 8-13, MM. J.A. Madec and R. Wan).

Plate 23 : Remnant of fossil algal crest on the south rim of Nukutipipi. Boundstone sample 1 m above low tide level was dated 3560 ± 100 years B.P. (Ref. plate : 1982 / 8-19, M. J. A. Madec).

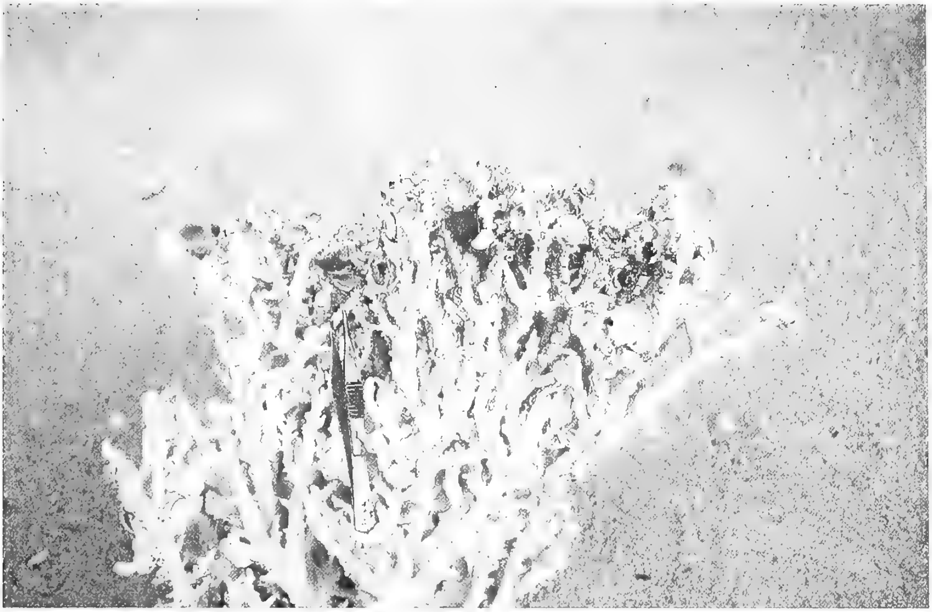


Plate 24 : Dead branches of *Acropora* constituting dome patch reefs in the lagoon. *Chama asperella* population fixed at the tip of branches (Ref. plate : 1988 / 7-19).

Plate 25 : Living and dead *Chama asperella* populations from the dome patch reef of the Nukutipipi lagoon (Ref.plate : 1988 / 7-20).

ATOLL RESEARCH BULLETIN

NO. 358

VEGETATION HISTORY OF WASHINGTON ISLAND (TERAINA), NORTHERN LINE ISLANDS

BY

L. WESTER, J.O. JUVIK AND P. HOLTHUS

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

CONTENTS

LIST OF FIGURES

LIST OF TABLES

VEGETATION HISTORY OF WASHINGTON ISLAND (TERAINA), NORTHERN LINE ISLANDS

BY

LYNDON WESTER,[1] JAMES O. JUVIK[2] AND PAUL HOLTHUS[3]

INTRODUCTION

Washington Island (Teraina) in the Northern Line Islands is a small atoll with a land area of 14.2 sq. km. situated at 4° 43'N, 160° 25'W. The Northern Line Island archipelago is comprised of four islands alined on an axis which runs from Christmas Island, just north of the equator, to Palmyra Island in the northwest (Figure 1). Washington Island, and its nearest neighbor Fanning Island, about 150 kilometers to the south east, have had close economic and social ties for most of their recent history. The climate of Washington Island is strongly influenced by intertropical convergence and has an average annual rainfall of 2902 mm although Christmas Island, two degrees south, receives only 766 mm.

Washington Island is lens-shaped and about 7 kilometers long by about 2 1/2 kilometers across at its widest point (Figure 2). The interior depression contains a freshwater lake and peat bogs and the ratio of the area of land compared to that of the enclosed water body is high. Similar small islands of this form would include Swains, Pulusuk and Clipperton Islands. Typically they have narrow fringing reefs which shelve very rapidly and do not provide safe anchorages. The Pacific Islands Yearbook describes Washington Island as "the most difficult and dangerous loading port in the Pacific" (Carter, 1984:257). The small size and inaccessibility of this island explains why, despite its unusual characteristics, it has not been investigated in more detail.

1. Department of Geography, University of Hawaii at Manoa

2. Department of Geography, University of Hawaii, Hilo

3. South Pacific Commission, Noumea, New Caledonia

The first map of Washington Island was produced by the United States North Pacific Exploring Expedition in 1874 (Figure 3)(Skerrett, 1873-4). Although a commendable achievement in surveying for its time, it has many inaccuracies but has been used as a base for most of the subsequent published maps (Wentworth, 1931; Bryan, 1942; Tennant and Mutter, 1977; Vitousek, et al., 1980). A map of the island at a scale of 1:4,800 in the Burns Philp archives at the University of Sydney shows sections used for harvesting coconut and was prepared sometime after 1915. Comparison with aerial photographs and ground observations indicate this map to be a more accurate representation of the shape of the island and the lake. Herms (1926) apparently used this as the base for his maps and we have done the same.

The purposes of this study were to survey existing vegetation patterns and summarize known information on the physical environment and history of human occupation as a basis for understanding the history of vegetation change.

In August 1982 Wester spent two weeks collecting and surveying vegetation on Christmas and Fanning Islands and a one day trip was made to Washington island. The following August the three authors spent two weeks on Washington Island. A total of nine transects were completed (Figure 4). These were selected to give typical cross sections of the island orto characterize particular places or circumstances and to sample the existing vegetation, topography and the character of the substrate. Peat samples were taken for pollen analysis to determine prehistoric vegetation change especially with respect to the role of coconut in the vegetation cover since there is uncertainty whether the species is native or a human introduction to the remote islands of the Central Pacific (Spriggs, 1980; Ward and Allen, 1980).

PHYSICAL ENVIRONMENT

Regional geologic setting,

Formation of the Line-Manihiki Ridge, on which the present Line Islands stand, began about 128 million years B.P. and continued until 105 or 80 million B.P. The ridge remained a submarine structure until between 85 and 80 million years ago when a pulse in crustal formation appears to have lifted the basaltic seamounts into the photic zone. Several reefs then developed simultaneously along the entire chain (Jackson and Schlanger, 1976; Schlanger and Premoli-Silva, 1981).

Subsequent cooling of the basement material caused slow subsidence which continues to the present. Those reefs able to keep up with the pace of subsidence created the present-day Line Islands, including Washington Island. A glacially induced sea level change during Oligocene time, 25 to 35 million years ago, perhaps resulted in the emergence of these atolls (Schlanger and Primoli-Silva, 1981) although Haggerty (1982) found no evidence for sub-aerial exposure of limestones in the Southern Line Islands.

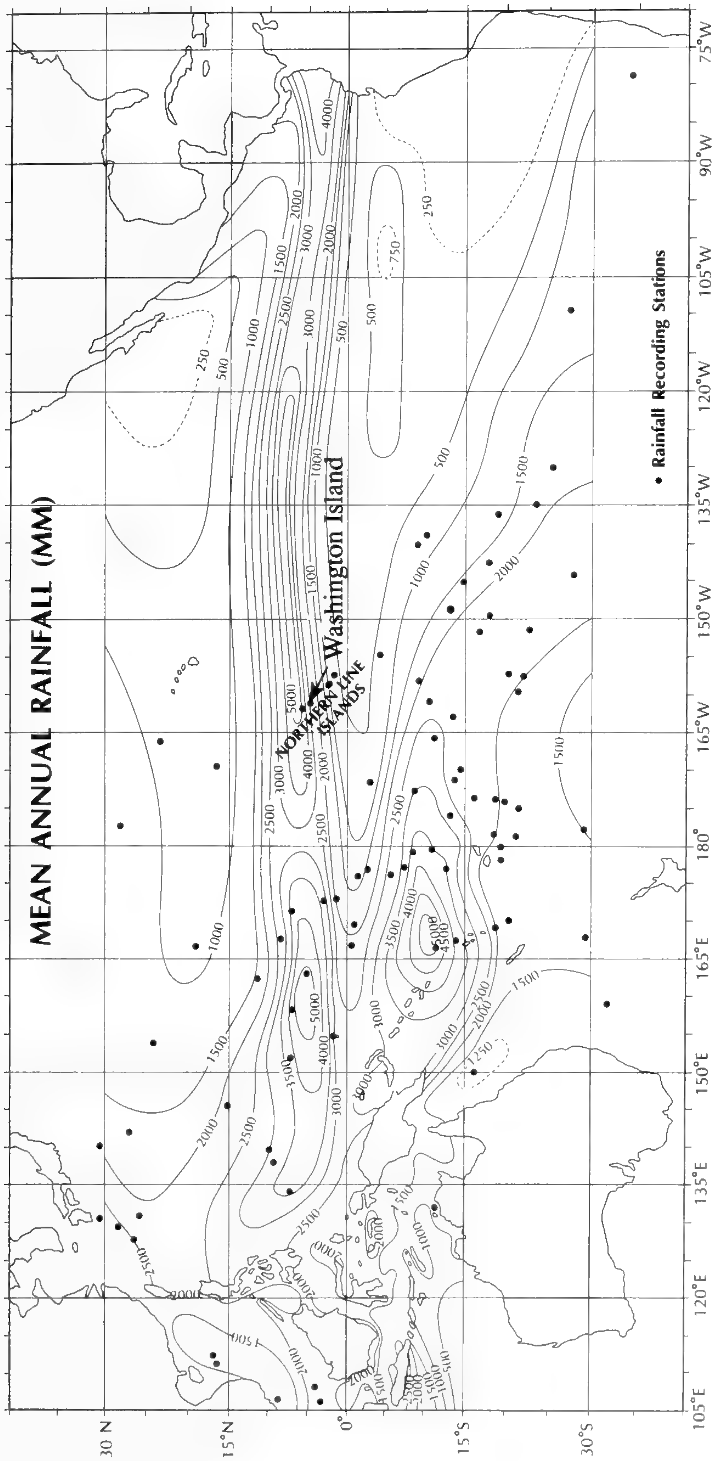


Figure 1. Location / Rainfall

Each of the Northern Line Islands has a distinctly different form. Christmas Island in the south is essentially a single large landmass enclosing a central lagoon and a few islets. Further north, Fanning is formed by three elongated motus forming the shape of a footprint. Washington Island is much smaller in area than the other two. Its reef platform is oval in shape. The freshwater body in the central depression has no natural connection to the ocean except at low points in the rim where water floods to the sea during time of high rainfall. Palmyra consists of a string of tiny motus in a horseshoe shape which barely protrude above sea level. Still further north is Kingman Reef which is completely submerged at high tide. The progressive decrease in elevation and size of the coral platform from south to north implies a tilt of the ridge or more rapid rate of subsidence to the north.

Terrestrial geomorphology of Washington Island

(a) Shoreline and Beach Ridges

A narrow beach composed of fine to medium sand mixed with swash deposits of coral rubble and reef rock debris surrounds much of Washington Island. Exposed patches of beachrock, up to 30 meters long, are found along the southeast and northeast shoreline. Although Wentworth (1931) noted the absence of gravel or shingle around the island's shores, scattered coral rubble and cobble were observed around the eastern end of the island during our investigation. Beach berms (or ridges) around all except the western end of the island are composed of coral rubble, cobble, and shingle typically ranging in size from 5 to 30 centimeters. Occasionally, larger reef blocks are incorporated into these structures. The coarse coral deposits making up the beach ridge may be covered by a layer of sand, with some gravel, especially on the seaward side.

The landward slope of the beach ridge is variable in topography. In some areas, the coarse cobble and shingle slope drops down fairly quickly and levels off at about 1 meter above the reef flat height, where it is overlain with highly organic, peaty material (Figures 5). On the northern and eastern end of the island the band of reef derived material may extend inland up to 400 meters but in the south the beach ridge is narrower but secondary ridges of cobble and shingle protrude through the the peaty soils of the island interior to form a discontinuous rings parallel to the coast. Around some parts of Washington Island, the beach ridge appears to be eroding. At the northeastern end of the island, which is most exposed to the prevailing easterly winds, a rampart is collapsing onto the beach and the root network, formerly helping to bind the ridge together, is exposed.

In places beach berms are poorly developed shallow pools of standing water are found along with freshwater seepage on the adjacent beach. These areas probably allow overflow from the lake and act as a natural control of the lake level.

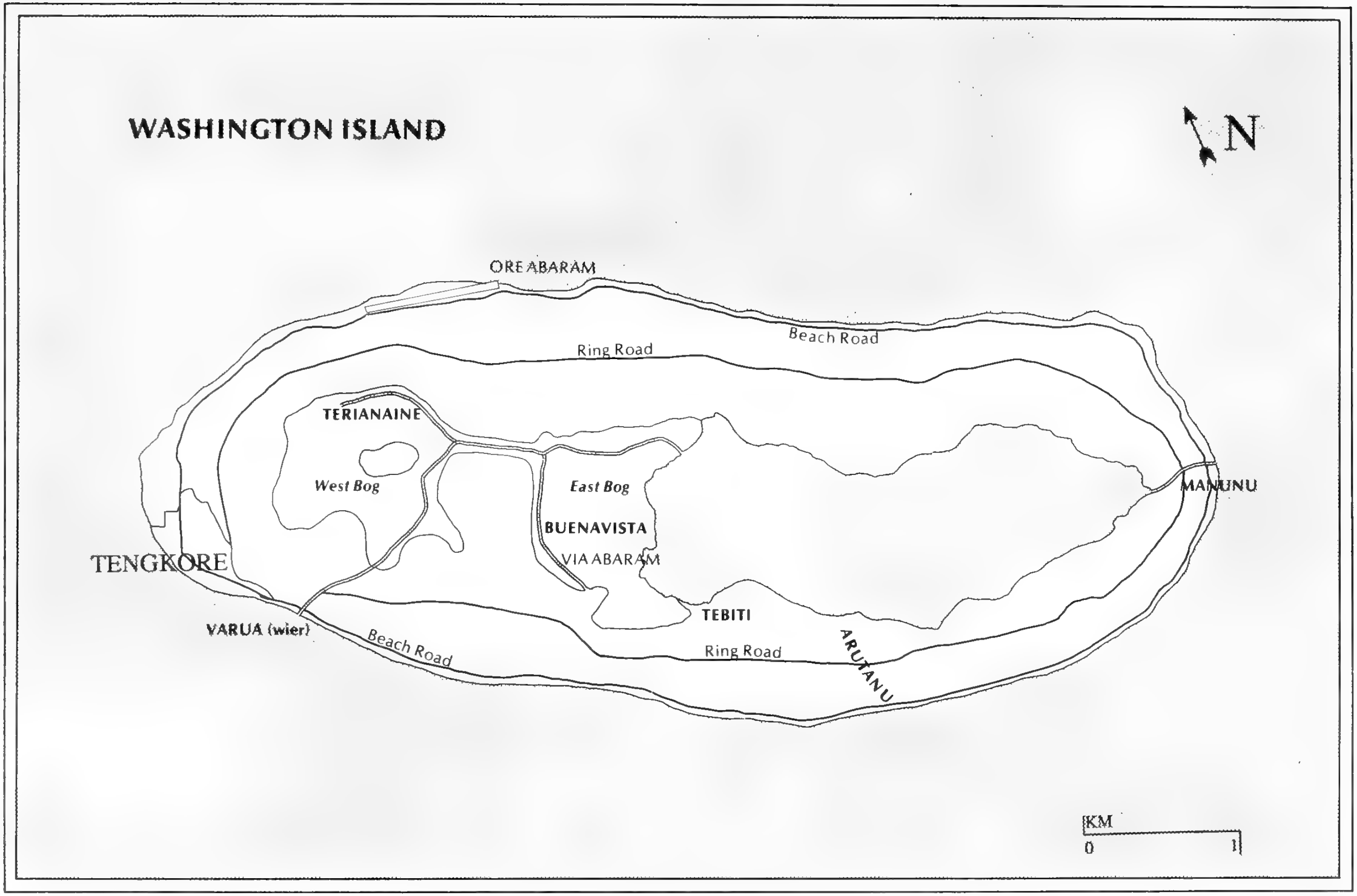


Figure 2. Place names

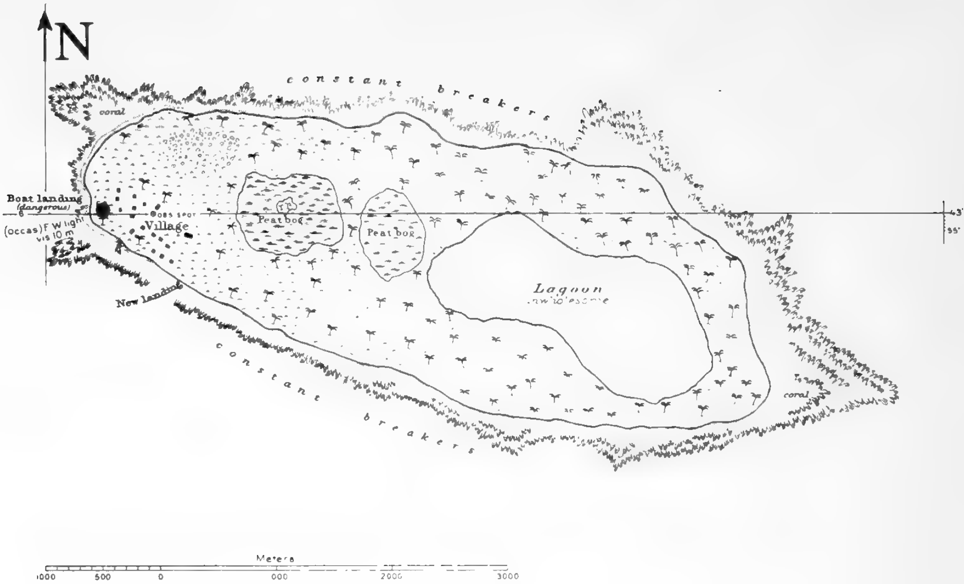


Figure 3. Chart of Washington Island prepared after North Pacific Exploring Expediton

Along sections of the southern shore fine sand deposits, colonized by <u>Tournefortia</u> shrubs, appear to overlie a series of broad, muted coral gravel and rubble ridges. Beaches of sand increase in width and height towards the western tip of the island as a result of westward shore drift along both the northern and southern shores (Wentworth, 1931). The convergence of the longshore drift patterns at the island's western terminus appears to be extending the land area in this direction, as evidenced by the clouds of suspended sand which are observed over the shoaling reef.

The lack of a distinct reef flat, an unstable depositional environment, and rough seas, made it difficult to make and accurate estimate of the extent of the sand deposits at the western end of the island. Wentworth (1931) describes the beach profile as a smooth cycloidal curve reaching a slope of 30 to 40 degrees at its upper end. He estimates its height at 12 to 15 feet, with an overall width of up to 200 feet, which is in accord with our observations. The beach sand deposits extend inland for over 150 meters from the water's edge. Their upper surface is increasingly stained by organic material with distance inland from the open beach. Steep berms, with wide ridgetops elevated about three meters above the reef flat, extend along the northwest and southwest sectors of the island. The backslope of the sand berm slopes down gradually until, at about 1.5 meters, it is ovelain by

muds and organic peats.

(b) Inland Beach Ridge and Peat Complex

On the west and southern side of the island the profiles reveal a series of concentric coral and rubble ridges which are presumed to be old beach ridges comparable to those found along parts of the present coast. In low areas, immediately behind the coastal beach berm, localized depressions may be filled with a soft, red-black to black mud, sometimes mixed with small amounts of sand or coarse coral rubble (Figure 5). Between the coral rubble ridges the land slopes gently towards the lake but lies between 1 and 1.5 meters above the adjacent reef flat. These areas are covered by tough fibrous peat-like material under coconut forest which is drier and firmer than the material which forms the substrate to the bog. The surface is lower than the reef deposit ridges, but 10 to 40 cm higher than the adjacent peat bog. Some lower lying sections hold standing water and may, at least in some cases, be abandoned babai pits or other excavations.

Along the northern side of the island, concentric ridges separated by peaty soils are not so evident. Instead there is a broad and slightly irregular platform 200 to 400 meters wide, formed of rubble and reefs of phosphate rock (Figures 7 and 8, Transects 1C and 7). The surface slopes gently towards the interior and until peat soils are encountered at a level of 1 to 2 meters above the reef flat, and extend inland to the lake or bog. In a few areas, the peat soils are found on gentle rises which stand as high as the rubble ridges along the shore (Figure 8, Transects 7). The forested islet in the western bog also seems to lie on a slight rise or irregularity in the underlying reef platform as we found the contact zone between the peats and the lagoon sediments below to be slightly higher under the islet than under the bog. This suggested to us that the islet may reflect an underlying structural feature of the former reef (Figure 5, transect 1b). Christophersen (1927, see his Figure 9) believed that the "bottom of the peat" was lower under the island than the surrounding bog, and also that the forested peat soil, was lower than the open bog. All our profiles suggest the dominant trend of the land surface in the island interior is downwards to the open bog community or lake shore. In this case also our findings do not agree with the those of Christopherson and we found no evidence of the raised peat sill or levee which enclosed the bog.

(c) Phosphate Soil and Phosphate Rock

Where Pisonia grandis trees occur on Washington Island, phosphatic hardpan and soils are found. The occurrence of phosphate rock in association with Pisonia trees, the chemical reactions involved, and the soils which result, are described by Fosberg (1954, 1957). On Washington Island, Pisonia, mixed with other species in varying amounts, is found around much of the island's perimeter. Some large trees even occur immediately behind the beach ridge crest.

Phosphatized sand, rubble-sized phosphate, and larger phosphatic rocks orsolid outcrops occur in association with Pisonia areas on the island.

Extensive sheets of phosphate rock hardpan are found at the surface in the Pisonia forest at the east end of the island and in the Pisonia and breadfruit forest just north of Tengkore village, at the island's west end. The large Pisonia woodland between the two bogs contains massive weathered phosphate blocks and outcrops, the upper surface of some reaching almost 1 meter above the surrounding ground level. Above surface phosphate is ascribed by Fosberg (1954) to have been pushed up by Pisonia root systems or heaved up by the roots of falling Pisonia trees. This explanation seems less plausible in this particular situation because of the amount of sub-aerial phosphate rock present, the size of the formation, and its height above ground level. However, no alternative explanation is proposed.

In any case, the presence of phosphatic rock material in conjunction with Pisonia trees leads to the development of particularly rich atoll soils, described by Fosberg (1954) as the Jemo series. The occurrence of phosphate rock on a very wet island such as Washington, is not well understood since most wet islands lack phosphate deposits altogether. As Stoddart (1983) points out, the distribution of phosphate rock suggests a variety of environments or complex environmental histories, may be involved and the occurrence of phosphate rock on wet islands may be an unusual deposit requiring special explanation.

(d) Peat Bog

Two large expanses of vegetated wetland on Washington Island are connected by a narrow drainage corridor and referred to as the East and West Bog. Other small depressions surrounded by coconut forest contain also contain bogs. The substrate is organic peat and supports growth of bulrush (Scirpus littoralis) (Christophersen, 1927).

West Bog was found to be about 1.3 to 1.6 meters above the adjacent reef flat (Figure 7, Transect 1) and slightly lower than the surrounding belt of coconut forest. An obvious drop of 10 to 30 cm was measured in the peat surface at the boundary between the forest and the open bog.

Judd (1859) described the bog as dry and firm and Christopherson (1927) noted the water table was 20-25 centimeters below the soil surface when he was there. However Streets (1877b) observed that the area was covered with water to a depth of six to eighteen inches. During our investigations the bog was covered by a few centimeters of standing water. East Bog bog differs in character from the western one in that there is evidence of degradation of the ecosystem. In parts the Scirpus seems to have died off and only dead roots and stem bases are evident. Christopherson also noted this so it is not a recent development. Some areas are soft and incapable of supporting a person's weight. This condition is very evident from photographs as well as the

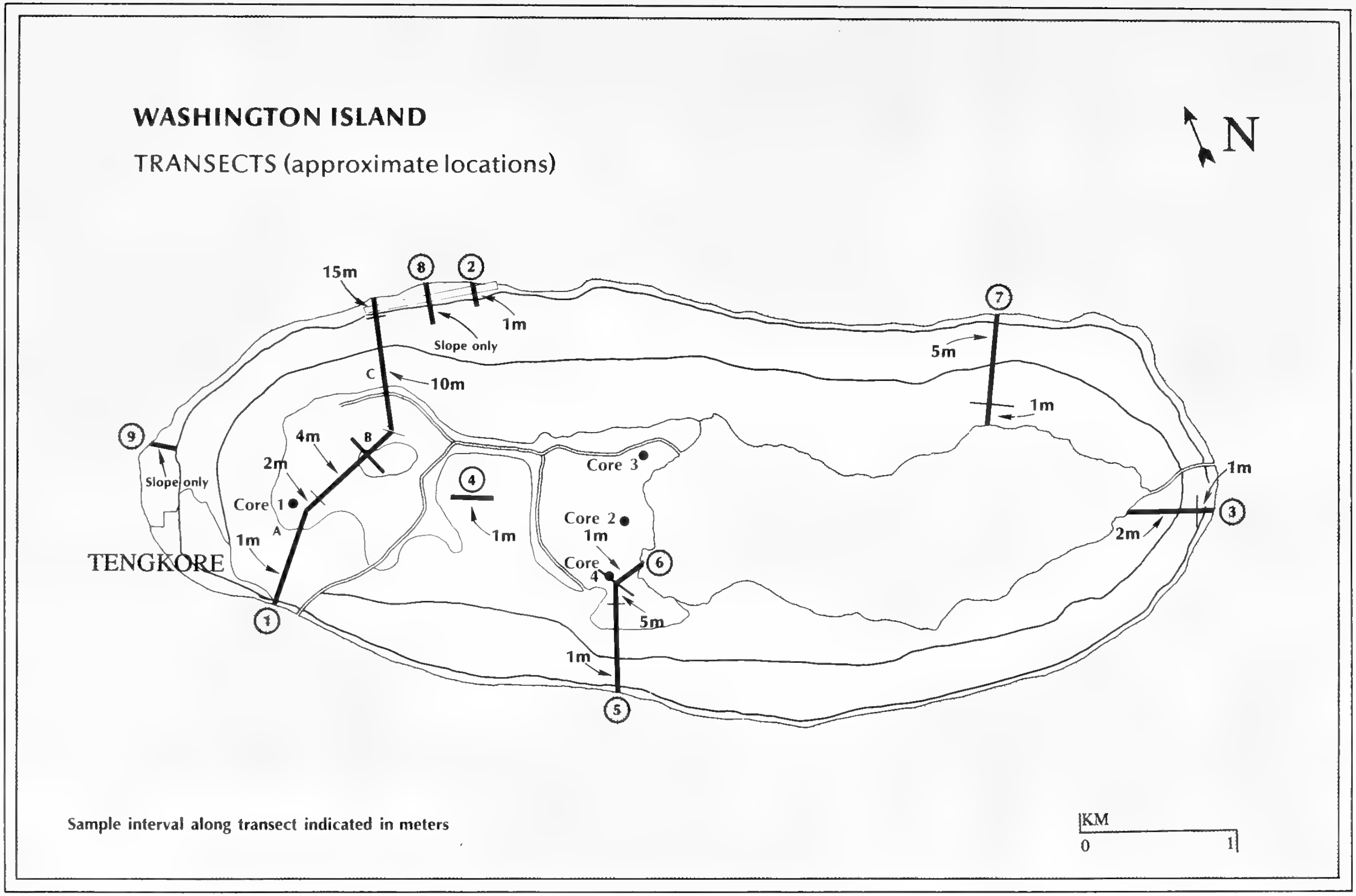


Figure 4. Transects and core locations

ground. Probes throughthe firmer peat revealed an under layer of slush which extended as far as our two meter corer could reach which impied at least part of the peat is floating.

Bordering the lake is a strip of much drier, firmer peat standing about 30 cm higher than the nearby moist Scirpus-dominated bog and supports patches of scattered coconut, Pandanus and fern. Christophersen (1927) felt that the lake was encroaching on the coconut forest and interpreted the fallen palms in the area as evidence of undermining and erosion by the lake. In contrast he also postulated successional encroachment of the Scripus-dominated bog first by Cyrtosperma and Cyperus, later to be followed by Polypodium and Pandanus, and eventually coconut. This sequence is normally observed along the gradient from the bog to the coconut forest. The presence of 'advanced' vegetation along the west or lake side of the eastern bog, he attributed to drift seeds and propagules having been blown westward across the lake to the eastern bog where they became established. The addition of the larger plants would result in the slightly raised peat bog level observed. An alternative explanation might be that the western end of the lake is controlled by the existence of a former ribbon reef that crossed the old lagoon. Structures of this sort are common in atoll lagoons and are evident in the present lagoon of Palmyra as well as in the lake on Washington. This reef provides slightly elevated substrate and suitable structural support for a narrow strip of trees along the lake edge.

Unsuccessful attempts to plant coconut in the western bog observed by Christopherson in 1925 were still evident in 1983 as vegetated rows of low, mounds.

Peat depth across the western bog was measured by Christophersen (1927) to range from 50 to 80 centimeters, with an average depth of 70 cm His probings revealed a maximum peat depth of 112 cm in other portions of the bog. Christophersen (1927) stated that the peat extends, with gradually diminishing thickness, about 170 meters into the coconut woodland from the bog's edge, which represents the distance that the forest species have advanced into the bog by the process of succession.

Our profile across the West Bog confirmed the peat to be uniformly 70 cm deep and overlying lagoon sediments of sand and clay (Figure 5), and quite consistent with Christopherson's findings. However cores in the East Bog reveal that the peat is much thicker and in parts the lagoon sediments lie more than 275 centimeters below the surface (Table 1).

The nearly uniform depth of the peat in the West Bog, and the fact that it lies on marine mollusk shells, implies that the peat bog has formed on a relatively shallow, level surface of a marine lagoon reef flat. This process may still be occurring in the northeastern portion of the lake where narrow reef flat remnants are covered with unconsolidated organic muck and dense Scirpus growth. The accumulated

Table 1. Depth of Peat

Core no.	Location	Maximum depth of peat (cms)	Underlying substrate	Radiocarbon dates		
				age	depth cms.	sample no.
1	West Bog	70	sand and clay	1060 ±100	64- 69	W5655
2	East Bog	275	not reached	860 ±110	255-275	W5686
3	East Bog	180	sand	1150 ±110	160-170	W5695
4	East Bog	145	sand	no date	---	---

detritus has not yet built up enough to form a peat substrate. The east bog presumably formed in deeper water of the central part of the old lagoon depression.

Measurement of bog level in relation to the lake's water level, or large standing pools of water in the surrounding woodland, show the bog to be 10 to 30 cm higher than the water. The construction of canals linking the lake and bogs and connecting them to the ocean, around the turn of the century, allowed the lake's water level to be controlled artificially and perhaps established a new base level. If the western shore of the lake is controlled by a reef structure, the cutting of the canal to the lake may have allowed water to penetrate into the peat and thus causing its degeneration. It is noted that the area of degraded peat is in the quarter where the canal enters the lake. Alternatively the floating peat of the East Bog may be an entirely natural, if slightly unstable, condition.

Lake formation

The formation of a fresh water lake on Washington Island has been the subject of speculation. We found marine mollusk shells and coralline sand beneath the peat and remnant reef structures with dead coral and marine bivalves in situ on the lake bed indicating that the present lake and peat bog were once part of a marine lagoon system.

There are numerous examples in the Central Pacific of low islands made up of a single land mass, like Washington Island. Quite a number of these reef islands have enclosed bodies of water, either ephemeral or permanent, in which salinity ranges from hypersaline or salty to brackish or fresh. Ephemeral or hypersaline lagoons have limited sub-surface exchange with ocean waters and their size and salinity depends on rainfall. Examples are found on Starbuck Island in the Southern Line Islands, and on Birnie, and Sydney, in the Phoenix group (Bryan, 1942). Other enclosed salt water bodies show obvious sea water connections by evidence of tidal fluctuations, direct observation of salt water surging through fissures in the reef platform substrate, or the presence of marine organisms. Among islands with this type of lagoon are Niutao and Nanumanga in Tuvalu, Malden Island in the Southern Line Islands, and Nikunau in the Gilbert chain (Holthus, pers. obs.; Bryan, 1942).

A few islands of the Pacific have enclosed lagoons of brackish or fresh water. Nassau Island, in the Northern Cook Islands, has a swamp-filled central depression with standing water that is fresh and drinkable (Bryan, 1942). Swains Island (Olosega), in American Samoa, is described as a partly raised atoll with an enclosed, shallow, brackish body of water (Cumberland, 1956; Whistler, 1983). Pulusuk, in the Central Caroline Islands, contains a 1 to 4 meter deep, brackish water lagoon, the bottom of which is covered with a layer of fine detritus. On Pulusuk, the lagoon was observed to be at least partly fed from the island's fresh water lens through a fissure in the limestone bedrock. Salinities ranged from 0.0

parts per thousand, just after a rain, to 2.8 parts per thousand (Nelson and Cushing, 1982).

Perhaps the best known example of a low island with an enclosed fresh water lagoon is Clipperton Island in the Eastern Pacific. In this case, the body of fresh water is relatively large and is surrounded by a narrow continuous strip of land which had an open surface channel in historical times and shows evidence of storm wave breaching (Sachet, 1962). Lagoon salinities at Clipperton range from fresh to brackish depending on the amount of rainfall and episodic washover by storm surf. The remains of coral and other marine organisms are found on the lagoon's reefs, which are veneered with mud (Sachet, 1962).

The lake on Washington Island was sounded for depth with a lead weighted line at a number of locations. Maximum depth was found to be about 10 meters, which agrees with earlier lake depth estimates of 30 feet (Wentworth, 1931). However, much of the lake is occupied by remnant reef structures approximately 1 meter deep. Aerial photographs show they form submerged, convoluted platforms and holes like many living reefs. On portions of the lake's northeast edge it appears that submerged reef flat is partly overlain by unconsolidated organic matter and other silt which is colonized by peat forming Scirpus.

The lake's water is very turbid. Although no macroscopic aquatic vegetation, such as is reported from Swains and Clipperton Islands (Whistler, 1983; Sachet, 1962) is found at Washington, the lake water is full of floating algal material. This material settles downward and forms dense clouds which grade into the viscous mud and silty material of the lake bottom. Water samples were taken at three depth intervals at the lake's deepest point. Results obtained from a salinity refractometer reveal the water to be completely fresh at all levels.

The process by which the enclosed body of water on Washington Island has changed from a marine lagoon to a fresh water lake is subject to debate. Neither is there mention of any such feature by earlier visitors to Washington Island. The extent of the land area separating the two water bodies also makes it unlikely that ocean waters have periodically breached the land rim. Christophersen (1927) supposed that the lagoon was isolated from the ocean by gradual emergence of the land. The salt water either evaporated or disappeared through sub-surface drainage and was replaced by fresh water from the island's abundant rainfall. Wentworth (1931) restated the emergence theory, adding that the process of freshening the salt water lagoon would have taken several hundreds of years. However, Huchinson (1950) points out that: "no elevated coral has been discovered in situ high enough to provide unequivocal evidence of emergence".

Elschner (1915), as reported in Hutchinson (1950), provided another theory for the lake's fresh water. He argued that guano material washed into the lagoon could result in the

precipitation of colloidal calcium phosphate. With sufficient guano, plenty of rainfall, and abundant organic detritus, this would result in the formation and deposition of a clay-like calcium phosphatic mud capable of sealing the lagoon from its subterranean connections to ocean waters. Over a period of many years, the island's copious rainfall would convert the system to that of a fresh water lake. The length of time involved in this process is indicated by the occurrence of a fresh water fish and eel species in the lake. Presumably, these animals were trapped as the salt water lagoon was isolated from the ocean. The conversion of the lagoon to a fresh water lake was so gradual as to allow the adaptation of these marine organisms to the fresh water environment, although the length of time necessary for this process to occur is uncertain.

The ability of guano deposits to form lagoon bottom substrate is supported by observations of Friederici (1910), as reported in Wiens (1962). On Niau Atoll in the Tuamotus, rain erosion of guano from the land rim allegedly resulted in the deposition of phosphate sediments up to 8 meters thick in the lagoon. Likewise, the water-filled depression on Enderbury Island is reported to be partially filled with "soft, muddy materials which are principally bird guano". Further evidence of the correlation between guano deposits and the formation of isolated bodies of water on reef islands is provided by those islands where the mining of phosphate has left artificial depressions. On a number of such islands, including Flint Island in the Southern Line Islands and McKean and Sydney Islands in the Phoenix group, the guano pits have become filled with rainwater, resulting in the formation of brackish ponds. In addition to phosphate deposition, the density of an island's reef rock platform may influence the retention of rain water. On Kili, a reef island in the Marshall Islands, persistent heavy rains lead to the accumulation of substantial amounts of fresh water in the island's central depression (Bach, 1950 as reported in Wiens, 1962).

The sealing of the bottom of the lagoon on Washington Island would account for a rise in the water level of the enclosed basin. Our survey showed the lake level to lie 70 to 170 cm above the inshore edge of the adjacent ocean reef flat (Figure 7 and 8). This roughly matches the approximate 1 meter submergence of the reef flats in the lake, which would have presumably formed to about the same base tide level as the ocean reef flat. Streets (1877b) reported the Scirpus bog was inundated suggesting perhaps the lake level was higher before the canals were constructed.

On the western end of the lake, we observed portions of the peat bog and coconut woodland peat being eroded. Christophersen (1927), interpreted this to indicate that the filling of the lake by peat formation had ended and statedthat: "the lake will now encroach upon the bog as the bog before encroached upon it". A reason for such a reversal

was not supplied.

The shallow sections of the former lagoon would be readily colonized by aquatic plants as soon as the the lagoon was sealed off from the ocean and the lake became sufficiently fresh to support them. The deeper water would receive some sediments but productivity levels in the murky water are low compared to the shallow sections supporting Scirpus. Soundings, which revealed depths of 5 to 6 meters immediately adjacent to portions of the eastern bog, suggest that the lake boundary is controlled by underlying reef structure and not the progress of ecological succession. The formation of peat would not be able to proceed any further than the edge of the shallow reef flat. Coconut palms which had germinated at the lake edge would lean out into the open sunlight of the lake, only to topple into it when their weight became too great to be supported at such an angle by roots anchored in the peat. This might give the impression that lake water erosion has caused the coconut trees to fall into the lake but in fact might occur on a stable shore line.

Climate

Sporadic collection of rainfall data began on Washington Island in 1910 but relatively complete data is available from 1946 to 1972 (Taylor, 1973 and Table 2). The average annual rainfall is 2902.7 mm. The wettest months are from March to June during which an average of at least 275 mm per month can be expected. August to November are generally drier but each have an average above 120 mm. Considerable variation is detectable from year to year and from month to month.

ARCHAEOLOGY

The islands of the Line and Phoenix group were uninhabited at the time of first European contact but there is indication that at least four of them once supported human populations. Two pieces of evidence for prehistoric occupation from Washington Island have withstood careful scrutiny. One was "a round enclosure of coral blocks about 12 feet in diameter inside" which was found on the western end of the island near the site of the present day village. This was described by an informant to Stokes (n.d.) and reported by Emory (1934). In the same area a basalt adze was found near the surface and was described by Finney (1958) who concluded it was decidedly Western Polynesian in character and similar in patination and form to those found on nearby Fanning Island. The styles of these artifacts are not of a sufficiently specialized type to be diagnostic (Bellwood, 1979). To understand their probable relationships it is necessary to consider the wider context of the Line Island archipelago.

The first European known to have visited Fanning Island was Edmund Fanning in 1798. Although he saw "no signs nor vestige of human habitation" himself, he recorded in theaccount of his voyages that, a few years after his visit, a

Table 2. Rainfall of Washington Island

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANNUAL
Mean	250.6	257.8	291.3	316.6	363.1	329.8	275.2	162.5	142.7	124.9	168.9	219.4	2902.7
Max.	938.0	787.9	1135.1	746.8	981.5	736.9	742.7	554.0	438.4	488.2	660.7	755.1	5181.9
Min.	16.3	6.3	17.8	99.8	59.7	112.8	76.5	9.7	1.0	5.6	0.0	2.8	1129.3

captain of one of his ships, who stopped at the island to procure beche de mer and turtle shell, discovered evidence of occupation.

> ... during this stay he [the captain] frequently walked into the interior, and in one of these walks he had come across some heaps of stones, which, to all appearance, from their order and regularity, were thus placed by the hands of men, although from the coat or crust of weather moss with which they were covered, it must have been at some remote date. Being prompted by curiosity, and a desire for further information upon this subject, he caused one of these piles to be removed, and found it to contain, a foot or two under the surface of the ground, a stone case, filled with ashes, fragments of human bones, stone, shell, and bone tools, various ornaments, spear and arrow heads of bone and stone etc. (Fanning, 1970:224-225)

Furthermore conspicuous evidence of human occupation was noted on Malden Island in the Southern Line Islands at the time of the first European visit to that island by Byron in the H.M.S. Blonde in 1825. Andrew Bloxam, the naturalist for the expedition, noted:

> "In one spot along the coast I observed what is evidently the work of human hands, though apparently of ancient date. It is a parallelogram of coral stones, with a pillar erected in the middle of a single stone 7 feet high. ... The Surveyor, who had walked to another part of the island, informed us that he had met with about 40 such buildings, but in a more perfect state, extending along the shore." (Bloxam, 1925: 80).

The presence of rubbish heaps, numerous structures, graves and house sites suggest occupation for a considerable period of time (Sharp, 1956).

Expeditions conducted under the auspices of the Bishop Museum in the 1924 and 1934 undertook archaeological surveys which were reported by Emory (1934, 1939). Emory himself did the surveys on Fanning, Christmas and Malden Islands, during the Kaimiloa Expedition in 1924, and visited Fanning and Christmas again in the course of the Mangarevan Expedition in 1934 but did not at any time visit Washington (Emory, 1984 personal communication). From Fanning he described dressed stone enclosures with L-shaped cornerstones and a slab lined tomb which he took to be of Tongan affinity. A. Sinoto (1973) investigated the sites himself at a later date and agrees that the structural style points to Tonga where coral and limestone are available and often used for construction, unlike the Marquesas where such materials are not available.

Four basalt adzes found on Fanning, along with the Washington adze, were likened by Emory to those found in Tonga and Samoa, and not similar to those found in Hawaii, the Marquesas, Tahiti, the Cooks or other marginal Polynesian

islands. However A. Sinoto (1973) notes that, since Emory wrote his opinion, similar forms have been found widely in Eastern Polynesia. Emory thought the fishooks which were recovered showed no clear relation to those of any other part of Polynesia but the presence of two holes in base and an upward projecting limb of the hooks suggested a connection with the traditions of the western Pacific. A. Sinoto (1973) notes however that identical forms have since been reported from the Marquesas. Finney (1958) seems to accept Emory's interpretation however Bellwood (1979) believes that both the slab lined enclosures and the fish hooks indicate an association with Penrhyn but he adds that we do not know enough to be dogmatic about it. A site studied by A.Sinoto yielded two radiocarbon dates which suggested occupation of one sites in the range AD 350-530 and the other the other AD 1020-1190. The 600 year discontinuity between settlements seems implausible and so sample contamination may have occurred (A. Sinoto, 1973).

Porpoise teeth, bored to be strung, were found in the Fanning tomb and present another problem. As they were employed extensively by the Marquesans but are rare in Polynesian groups elsewhere, Sharp (1956) concluded that the Line Islands were occupied by Marquesans. These people he imagined were carried by chance on prevailing wind and ocean currents, at an early period before Marquesan culture had much opportunity to differentiate.

A species of parrot, the Polynesian lorikeet (Vini kuhli), was found on Washington and Fanning Islands at the time of first European contact. The only other place where this particular species of lorikeet is found today is Rimatara and Tubuai in the Austral Group. As these birds were favorite pets of Tahitians (Bruner, 1972) one possible explanation of this remarkable disjunction is that they were introduced to the Line islands by Polynesisns and have since established wild populations. Related species of Vini occur in the Society Islands and the Marquesas. Although today they are all rare and in danger of extinction, they were once widely distributed through eastern Polynesia.

A. Sinoto (1973) recognized that with small amounts of data many questions were left unanswered including the annomaly that the structural styles discovered on Fanning implied Tongan connections whereas artifacts indicated Marquesan affinities. However he tentatively proposed that decendants of proto-Polynesians who had settled in the Marquesas, but retained some of their earlier cultural attributes, set off on a migratory voyage sometime between AD 400-1100, but most likely after AD 600, and settled on Fanning Island until abandonment or extinction took place. Kirsch (1984) esentially accepteds this reconstruction of Polynesian dispersal.

In 1906 a fragment of a canoe was found on Washington Island when a canal was being dug between the East and West Bogs for the purpose of transporting copra (Stokes n.d.).

The canoe was buried beneath several feet of peat and was thought to made of Callophyllum, which had only recently been introduced to the islands. Emory (1934) concluded that it was of prehistoric origin. The fact that it contained nails was explained as a later repair. An annotation of the record card, citing Douglas Yen as the authority, states that the canoe was either constructed of Pisonia, which is native to the island and present in considerable abundance, or breadfruit, which was probably introduced at an early date. Furthermore the age of the wood has been estimated to be 160 $\pm$ 100 by radiocarbon dating (Preston, Person and Deevey, 1955). This would suggest it was constructed by Polynesian laborers in the nineteenth century but how the canoe came to be buried is still to be explained. Stokes (n.d.) recorded that it was found under four feet of peat whereas a newspaper account by Resterick (1929) stated that it was found eight feet down. In any event it could hardly have been covered to either depth by natural sedimentation in the forty years since first settlement.

Oral histories suggest that Polynesians to the south may have been aware of the existence of the Line Islands and have visited them.

> There is a Manihiki tradition which relates that natives of Manihiki frequently visited Washington Island at a time when it was inhabited. They called the island Arapata and a legend records how it was overwhelmed by a cataclysm. A native of Manihiki, on a visit to Washington Island, once asked for a fish called malatea (Cheilinus undulatus or giant wrass) and was given only the head. Insulted by this, he left in his canoe, and cursed the island which then turned upside down and malatea has not been found there since (Emory, 1934; Stokes, n.d.).

The view that most of the Polynesian islands were populated by chance drift voyages has been taken by Sharp (1956, 1963) who characterized the Line Islands as lonely islands; a haven for unfortunates blown away from their home islands and cast up on these remote atolls. Here, with sufficient water and food they could live out their solitary lives practicing their traditional livelihood. He conjured a melancholy picture of a canoe load of castaway men on Fanning Island making simple tools with the materials available and burying their dead in the ritual way, until the last one died. This image was developed into an evocative short story by Updike (1973). Sharp went further to speculate that a canoe containing women may have drifted to Malden Island allowing a population of several generations to persist there. However recent reassessment of Polynesian navigation skills make it appear distinctly possible that prehistoric navigators conducted purposeful voyages of exploration and possessed the skills to identify the location of their discoveries so as to be able to make repeated voyages. Under

these circumstances the Line Islands might have been supply islands or revictualling stations, between eastern Polynesia and Hawaii as early as 400 A.D. (Kirsch, 1984).

In summary it can be stated that the Line Islands were visited in prehistoric times by Polynesians. Colonies appear to have been established on Malden for an extended period of time and perhaps also on Fanning. Occupation of other islands, including Washington, may have been of shorter duration or by smaller populations. Archaeologists are divided in their opinion of the origin of the Polynesian culture found in the Line Islands. Both eastern and western Polynesia have been proposed on the basis of existing evidence. The resolution of this paradox will probably have to await either the discovery of more archaeological material in the Line Islands or a better understanding of the mother cultures in the South Pacific.

HISTORY

Edmund Fanning sighted Washington Island on June 12th. 1798 and was the first European discover of both Washington and the island that bears his name. Although no landing was made on Washington he left a glowing account of it:

> This was of much greater elevation than Fanning's Island, and was, moreover, covered with plants or grass, presenting to our eyes a beautiful green, and flourishing appearance. With the unanimous approbation of every individual on board, both officers and seamen, and with feelings of pride for our country, we named this, Washington Island, after President Washington, the father of his country. Having but recently obtained a bounteous supply of refreshments, there was no necessity for our making a landing here, although the trees and green foliage, among which we plainly saw the tall coconut-tree, presented a very strong inducement for us so to do, but we passed it to the south, we then steered to the west. ... There can be no doubt that at this island a vessel might obtain an abundant supply of excellent refreshments for her crew. As at Fanning's Island, so here, we could perceive no tokens of its being at all inhabited (Fanning 1970).

It is entirely likely that his good report resulted in other visits in the early nineteenth century by traders or whalers. In 1814 a map published by Martin Arrowsmith (Stanton, 1975) showed and island with the name New York at the approximate location of Washington Island (Wilkes, 1970) suggesting an independent discovery. Gardner, in the ship Bowditch, sighted the island in 1833 (Table 3) and tried unsuccessfully to send boats ashore to collect coconuts. In his log he drew of profile of the island which depicted a low

Table 3. Visits of Ships to Washington Island

YEAR	MONTH	SHIP	CAPTAIN/ LOGKEEPER	COMMENTS
1789	Jun	Betsy	Fanning	named for George Washington
1833	Sept	Bowditch	Gardner	sighted island PMB* 833
1833	Oct	Bowditch	Gardner	tried to send in boats for coconut but could not; profile drawing of island.
1840	Dec	Peacock	William L. Hudson	in company of Flying Fish as part of U.S. Exploring Expedition; established position but did not land. PMB 773
1840	Dec	Flying Fish		in company of Peacock on as part of U.S.E.E.; sighted but did not land; PMB 773
1846	Sept	Acushnet		sighted island; PMB 215, 737
1847	Dec	William & Eliza		sighted island; PMB 837
1848	Jul		Lucett	described from sea (Lucett, 1851)
1849	Nov	Pioneer		sighted island; PMB 888
1854	Feb	Washington	Holley	boats sent ashore and returned with sweet potatoes, coconuts and bananas. PMB 369, 370
1855	Nov	Rambler		sighted island; PMB 862

Table 3. Visits of Ships to Washington Island (cont.)

YEAR	MONTH	SHIP	CAPTAIN/ LOGKEEPER	COMMENTS
1856	Dec	Petrel		sighted island; PMB 887
1857	Nov	Triton 2nd		sighted island; PMB 869
1858	Dec	Cicero		sighted island; PMB 231
1859	Sept	Josephine	W.C. Stone	claimed for U.S. and American Guano Co. (Judd, 1859)
1861	Dec	Massachu- setts	Daniel B. Greene	Natives had been there a short time; fished, traded for coconuts. PMB 349
1864	Dec	Adeline		sighted island; PMB 304
1866	Nov	Onward		sighted island; PMB 898
1867	Dec	James Maury		sighted island; PMB 335, 336
1874	Jan	Portsmouth	Joseph S. Skerrett	North Pacific Exploring Expedition; surveyed island; (Skerrett, 1873-4; Streets, 1877a)
1875	Jan	Arnolda		sighted island; PMB 721
1875	Mar	Arnolda		sighted island; PMB 721
1879	Jan	Helen Mar	Koon or Deshon	landed passengers and lumber; PMB 244
1889	May	Cormorant	Nichols	annexed for Great Britain

* Pacific Manuscripts Bureau document see Langdon (1978)

shore lined with palms.

Before longitude could be fixed accurately the same island was often reported in several different positions under different names. At least five islands had been reported in the vicinity of Washington Island and Commodore Wilkes of the United States Exploring Expedition dispatched two ships in December 1840, under the command of William L. Hudson, to investigate the area. They searched five different locations and were satisfied that there was only one island. Like Edmund Fanning, and probably others before him, Hudson did not attempt to land because of the absence of a safe anchorage. However he left a description:

> It is three and three and a quarter miles long by one and a fourth wide, and is entirely covered with cocoa-nut and other trees, exhibiting a most luxuriant growth. There is a reef off its eastern point, which extends for half a mile. At the western end, a coral ledge extends two miles in a northwest-by-west direction, on which the water appears much discolored, but the water was not seen to break upon it, except close to the point of the island. The island is elevated about ten feet above sea level. The surf proved too heavy to allow of their landing and the island affords no anchorage (Wilkes, 1970).

This did not dispel the errors regarding the position and name of Washington Island as Edward Lucett, a trader, searched for "Prospect Island" which appeared on his chart at the same latitude as Washington but 80 miles to the west. He concluded that they were one in the same. He also was deterred from attempting a landing and left a description; presumably based on what he could see from his ship.

> It is about three miles long, and rather more than a mile in width; elevated from twelve to fifteen feet above the level of the sea; and its surface presents an unbroken mass of vegetation. A deep verdant foliage forms the basement to columns of cocoa-nut trees, which rear their tall shafts in such seried ranks, the eye could not penetrate them. We endeavored from the masthead to ascertain if any lagoon existed, and believed not. Surf breaks close to the beach all round the island; dangerous landing for boats. Green water runs off the west point, in a north-west by north direction, for nearly two miles, but we saw no breakers except those on the sandy beach. Sailed over part of the green water; bottom was clearly discernible - white sand and patches of coral. Made no attempt at landing, from the uninviting aspect of the surf. Birds seemed the sole tenants of the island; they flocked around us in great numbers, and the beach was swarming with them - a certain sign of the absence of that carnivorous animal, man (Lucett, 1851).

These early descriptions are of interest because they establish that coconuts were present on the island before Europeans arrived. The impression that these accounts leave is that the coconuts were abundant and not just a fringe along the shore however since no landings were made the inland extent can not be established.

From the earliest times the history of Washington Island was tied to that of Fanning. The latter had a larger land area and, perhaps most importantly, it had a safe harbor. Thus Fanning Island was always the center of operations and Washington Island was relegated to the position of a satellite. Although there were attempts as early as 1820 to establish a colony on Fanning by one Navarro, a Captain Green, Mr. Dean and 37 Hawaiians, it apparently failed because by 1822 most of the party had returned (Maria Loomis, 1819-24; Elisha and Maria Loomis, 1820-24; Restarick, 1929a). Whalers and traders who stopped on Fanning Island during the 1840's reported castaways or the presence of small groups attempting to settle (Wester, 1985). It would seem that Washington Island had been colonized by 1854 because when a whaler stopped there he reported trading for "sweet potatoes, coconuts and bananas" (Holley, 1853-57). It is not clear who founded this colony but it is evident that it did not persist.

In 1852 Henry English acquired Fanning Island from Charles Burnett Wilson who had inturn purchased it from Messrs Lucett and Collie who had established an enterprise to produce coconut oil on the island. English intended to continue this work and provide supplies for whalers and traders (English, 1857). In 1857 William Greig, a Scot who had a dry goods store in Honolulu, went to work for English as Assistant Manager of Fanning Island. English formed a partnership with William Greig and James Bicknell in 1859. The coconut business changed from oil to copra and prospered. Operations eventually branched out into several other endeavors including guano, beche de mer, ship repairing, victualling and honey production (Anderson and Kelly, 1980).

In the 1850's considerable interest developed in the dry islands of the Central Pacific as possible sources of guano. In 1858 a newspaper article (New York Tribune, March 5) listed 48 islands which were claimed as U.S. possessions on the basis of an Act of Congress passed in 1856 (United States Congress, 1859) allowing U.S. citizens to claim islands which were not inhabited or under the jurisdiction of any other government and on which guano was present. Among this list was "Prospect Island" which is believed to be a synonym for Washington (McClellan, 1940; Motteler, 1986). It is not clear which individual visited Washington and claimed it for the United States. However it is evident that Americans were actively seeking guano islands in the region because in 1857 Henry English appealed to the British Consul in Honolulu for permission to "hoist the British flag as protection to his Property" (Miller, 1857). In recommending approval to this

request to his superiors the Consul noted that HMS Dido had touched on Fanning in 1855 and obtained "a supply of fowles". In 1859 Gerrit Parmile Judd, an American who had become a naturalized Hawaiian citizen, sailed to the Line Island as an agent for the American Guano Company to press claims. They stopped on Washington Island (referring to it as New York Island) between August 1st. and 3rd. 1859 and made one of the earliest descriptions of the island from the land. He makes no mention of any inhabitants so it must be assumed that the colony, which had been present in 1854, had been abandoned.

> Sept. 1 1859 Went ashore. Went through corner of the island, came out on north shore.
> Sept. 2. 1859 Set out to find the lagoon. Came out of trees to the south. Walked to east or windward side and found self in a forest of large, tall and stately trees - 10 ft. through (Babian) - Pursued as thought straight course blazing trees - but came on track a second time. Set off in another direction and came on lauhala and coconut trees and in less than an hour found lagoon -1000 acres covered with rushes but dry. Took a few specimens - one from the lagoon where small birds had nests, - no phos-lime; 2 from near beach - Phos. and lime.
> Sept. 3 1859 Took possession of island in the name of USA and Am. Guano Co. Put a document in bottle and hung from a tree. Came aboard. "Adieu to New York Island, a beautiful spot capable of sustaining 1000 natives" (Judd, 1859).

Despite the encouraging report, the American Guano Company focussed its operation in the Southern Line Islands and paid no more attention to Washington.

Permanent occupation of Washington Island appears to have been the result of expansion of Henry English's operations from Fanning in 1860 (Stokes n.d.). This is confirmed by a log kept by a number of people, including possibly Henry English (Palmer, 1973), and a whaler who stopped there in 1861 and noted that the natives could provide nothing because they had only been there a few months (Greene, 1860-65). In 1864 English sold his share of the islands to Greig and Bicknell and left because of ill health. Greig took charge of Fanning while Bicknell managed Washington Island. They imported laborers from various parts of the Pacific. In 1874 it was reported that "Tahitian" laborers were used (although this term is often used loosely for any Polynesian indentured laborers). However it was noted by James Bicknell, the nephew and later heir to his uncle's share of the operations, that Manihiki laborers were used in 1882 but in 1894 the laborers were Gilbertese (Stokes, n.d.).

Another search for guano was made in 1878 this time by John T. Arundel a British trader and guano digger who later became one of the principle shareholders in the Pacific Phosphate Company which later mined the deposits of Nauru and Barnaba (Ocean) (Langdon, 1974). With the assistance of Greig and Bicknell he surveyed both Fanning and Washington Islands

and, while on Washington, made the following notes in his diary:

> Arrived Washington Tuesday (Nov. 12) ashore by 10 am. Went with Bicknell to lake - slept there. Went to see guano at the weather end of the island. Returned to lake house for breakfast. Afterward walked home calling on route at guano bed where ape grows. Took a lot of samples. Left at about 5:30pm. (Arundel, 1870-1919).

As a result of these surveys Arundel undertook a guano mining operation on Fanning between 1878 and 1880 and some digging continued until 1885 (Republic of Kiribati, 1983). However no evidence can be found of an attempt to exploit the deposits on Washington. It may have been because they were of inferior quality or because the island itself was less accessible.

In 1874 the USS Portsmouth under the command of Joseph S. Sterrett was dispatched to Palmyra, Washington and Christmas Islands Island as a part of the North Pacific Surveying Expedition for the purposes of surveying the islands and to ascertain if Prospect Island, shown close to Washington Island on some charts, did in fact exist. They spent January 1st. and 2nd. surveying Washington with steam cutters from the ocean and with a landing party on shore (Skerrett, 1873-4). Thomas H. Streets, the Assistant Surgeon, left the first scientific description of the island. He noted that, as a result of recent heavy rains, the bogs were covered with water to a depth of six to eighteen inches. He reported the existence of a species of eel and a shrimp in the lake as well as the Polynesian lory, a warbler, like that on Christmas Island, and a new species of duck which was described on the basis of the specimens he was able to obtain. He also collected plant specimens which are presently preserved in the National Herbarium, Washington D.C. (Streets, 1876, 1877a, 1877b).

Confusion about the position, name, and number of islands in the northern Line group persisted for many years in publications and on maps and charts (Behm, 1859; Findlay, 1884). The British claim to Washington Island was reinforced by a landing on May 29th 1889 by Commander Nichols in the HMS Cormorant at which time it was formally annexed.

George Bicknell died in 1884 leaving his share of the plantation to his brother, James Bicknell, then the auditor of the City and County of Honolulu. However William Greig continued to operate the copra production industries on both islands with his large family of four sons and five daughters until his death in 1892. The elder son George Greig took over the management. James Bicknell remained in Honolulu and was considered half owner of the islands by the Greigs. In 1903 Humphrey Berkeley obtained an option to purchase Bicknell's share in the islands and attempted to interest the English company of Lever Brothers in acquiring them. Levers wished to obtain copra plantations in the Pacific to supply their soap manufacturing business. They were discouraged from taking

action when it became clear that Berkeley could convey clear title to the property. It appeared that Bicknell's interest was an undivided half share which was entailed. Meanwhile the heirs of the estate of William Greig were disputing the execution of the will and eventually engaged in a legal battle which resulted in a court case heard in Suva, Fiji in 1903 (Unilever, 1903).

In the same year George Greig disposed of his interest in the company and a younger brother William (Willie) became the manager and his brothers David and James remained to assist. Financial difficulties, already apparent before the legal battle, reached a head in 1907 and 1908 when creditors took legal steps to obtain the return of the money they had advanced. Proceedings in Suva resulted in the sale of both Washington and Fanning Islands for debt. The purchaser was a French priest, Petrico Emmanuel Rougier, who had renounced his ministry and became a plantation owner (Anonymous, 1958). He organized Fanning Island Plantation Ltd. which included both islands and eventually resold them at a considerable profit to a British syndicate represented by C. M. Armstrong. Greig family members continued to work on the plantation at least until Hugh Greig died on the Fanning Island in 1956 (Palmer, 1956). The family was on Fanning Island when it was attacked by a German warship during the First World War. The objective was of course the Cable Station which was an important link in the trans-Pacific communication line established across the Pacific between Sydney, Australia and Vancouver, Canada in 1902 (Restarick 1929b).

Washington and Fanning were purchased in 1935 by Burns Philp Co. Ltd., of Australia. They operated them as a copra plantation under the name of Fanning Island Plantations Ltd. until 1983 when they sold the islands to Kiribati Republic. Since that time the price of copra has fallen and harvesting of coconuts has been intermittent on Washington Islands. The government of the Republic of Kiribati is meanwhile investigating the economic potential of the islands for future development (Republic of Kiribati, 1983).

VEGETATION

The earliest recorded description of Washington Island were from the sea from which vantage observers agree that it was lushly vegetated and that coconut was a prominent feature. The first known account of the island from the land reported forests of "Babian" (Pisonia) as well as coconut and Pandanus (Judd, 1859) as is found today. However groves of Artocarpus (breadfruit), occasional banana, extensive tracts of Cyrtosperma and large Ficus, often marking abandoned camps, are reminders that the island has been manipulated by humans for the last 130 years. A map in the Burns Philp archives indicates the extent of coconut planting in the early decades of this century. Except for the cleared areas around villages

and abandoned camps, road and canal sides, the vegetation of Washington Island has the outward appearance of being a natural vegetation community especially since the harvesting of nuts has ceased. The navy chart produced by the North Pacific Exploring Expedition in 1874 implies the whole island, other than the bogs, was essentially covered by coconut (Figure 3). A patch of some other vegetation is indicated at the western end of the island which corresponds with a present day stand of large Pisonia, and lends credibility to the accuracy of representation of vegetation on the map.

Methods

For the purposes of making a general description of the vegetation of Washington Island, and in the absence of existing aerial photography, a set of oblique aerial photographs were obtained using 35 mm color print film during an over flight in a small plane. A preliminary analysis of the photographs was done before going to the island and conspicuous vegetation entities were identified. Ground surveys were conducted in August 1983 with the purpose of characterizing the observed vegetation patterns. One meter wide belt transects were run between the beach and the lake or bog (Figure 4) to include a maximum number of patterns identified from photographs. The sample interval along the belt transects varied. Near the shore, where transitions were sharp, each square meter was sampled; as the vegetation became homogeneous, such as in the closed coconut forest or across the bog, the interval was extended to every two, four, five, or ten meters. At each sample site the substrate was noted. The topography was surveyed with the use of a transit and pole. A final vegetation map (Figure 6) was drawn with reference to the uncorrected aerial photographs, data obtained from transects, photographs taken on the ground and general observations.

Voucher specimens of all native, adventive and cultivated plants were made. These specimens have been placed in the herbarium of the Bishop Museum, Honolulu and reported by Wester (1985).

General Description of the Vegetation

The transecting technique is useful to interpret the patterns observable from aerial photographs and give a realistic impression of the gradational character or homogeneity of plant assemblages. Transect data of this sort does not lend itself to statistical analysis but for the purpose of this study, the identification and description of broadly defined types, it is quite satisfactory (Figure 7 and 8).

Today most of the island is luxuriantly wooded with coconut and other trees as it appears to have been in the nineteenth century. A survey of the terrestrial vascular flora revealed a total of 91 species of which 25 were considered indigenous. Others were cultivated species (46) or adventives (20) (Wester 1985). Adventive species were mostly concentrated around the village, along roads or paths or other

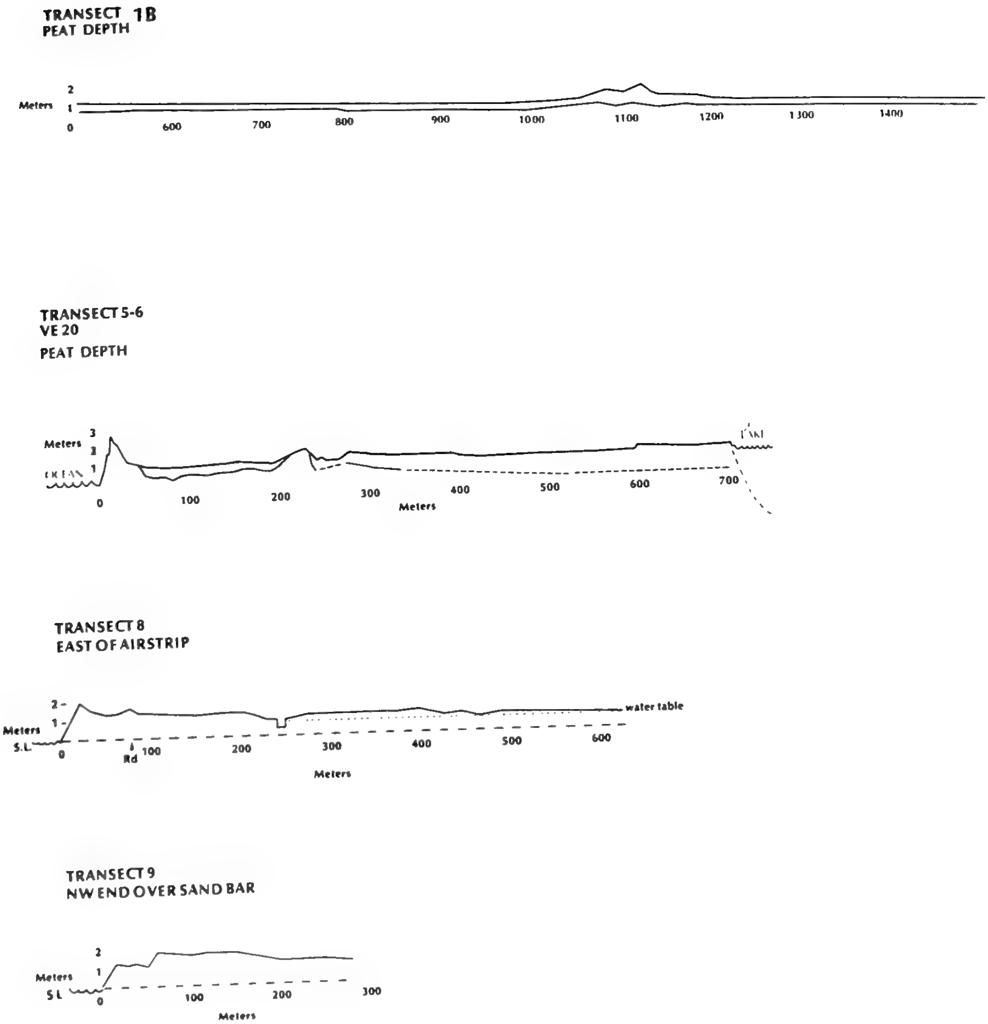


Figure 5. Island cross-sections

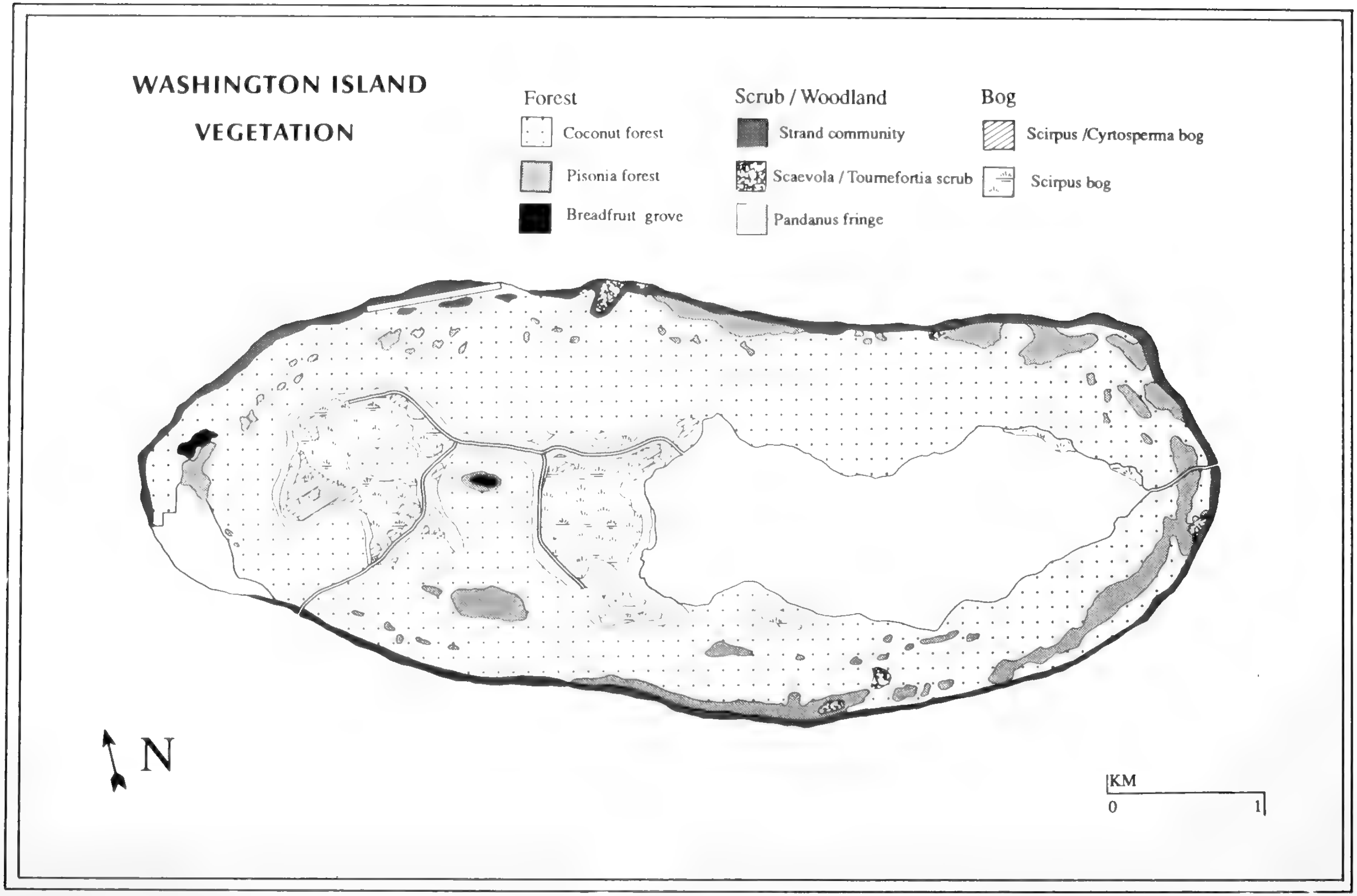


Figure 6. Vegetation

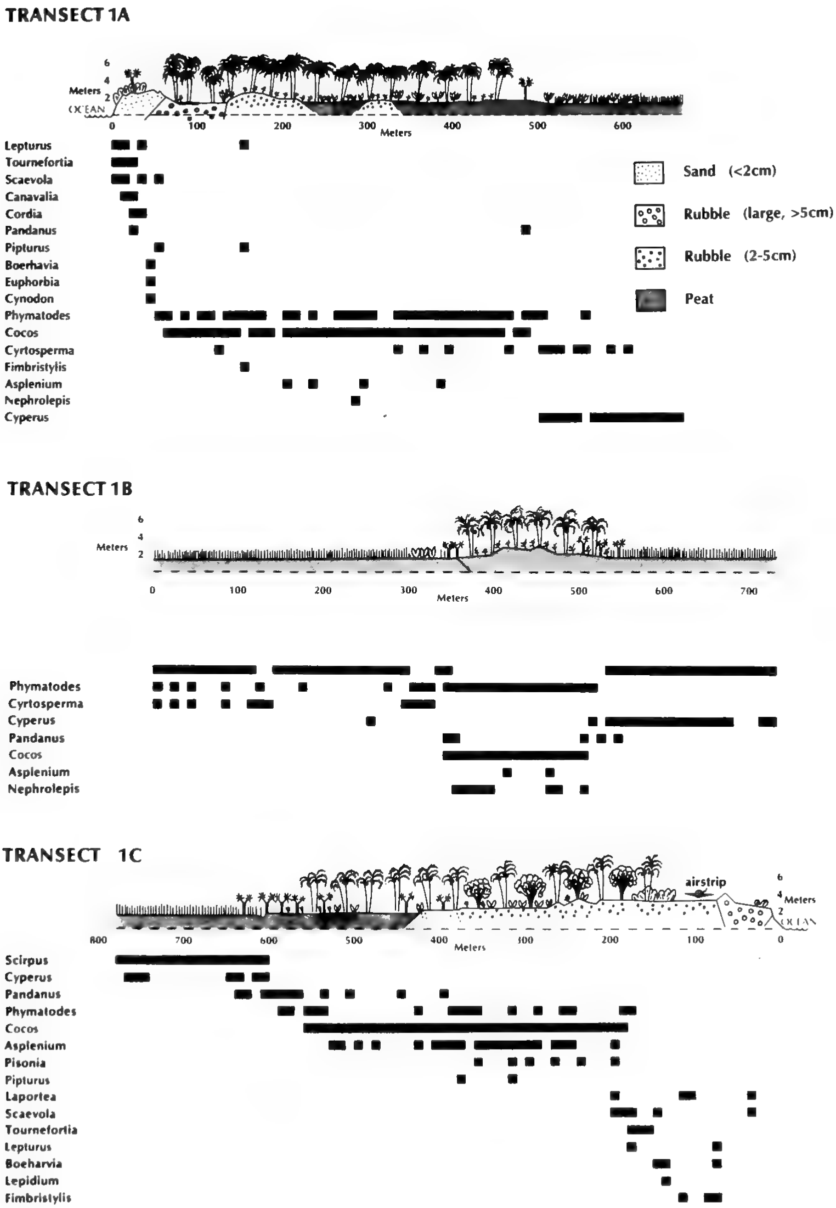


Figure 7. Transect 1A, 1B, 1C

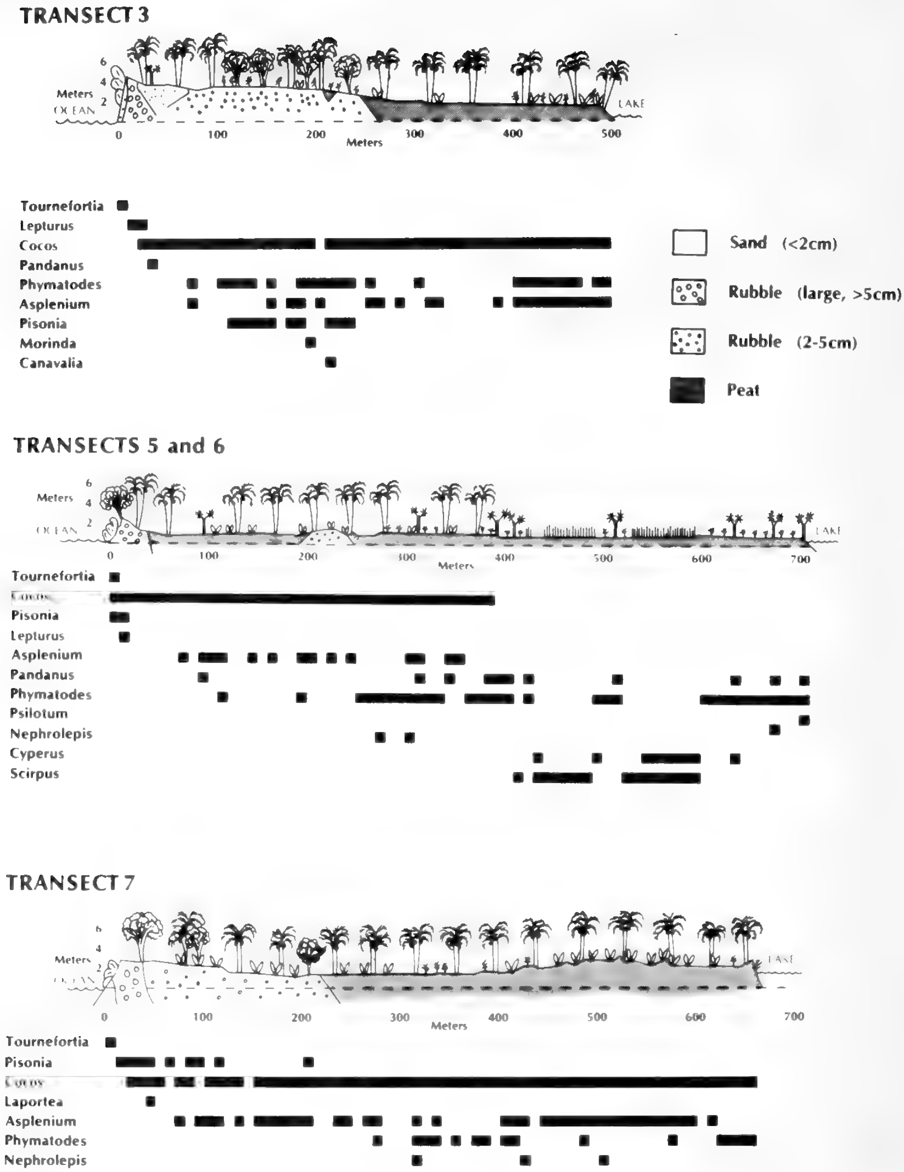


Figure 8. Transect 3, 5 - 6, 7

disturbed areas such as former temporary camps, roads and the airstrip. These areas were largely excluded from this study. The main non-forested terrestrial habitat is the bog whose herbaceous flora is most distinctive and separated from the other communities by a very narrow ecotone.

The forested areas are largely dominated with Cocos with admixtures of other species which could be sometimes extensive, such as Pisonia, or in other instances highly localized as in the case of some breadfruit forests. Closed canopy communities of this sort cover 80% of the land surface.

Ecotonal communities include the narrow ring of strand vegetation that skirts the coast, and which is characterized by the presence of Tournefortia with a the rich understory. In certain places no tree layer is present at all and instead dense thickets of Scaevola have become established. Also ecotonal in character is a narrow zone separating the forest and the bog communities, presumably susceptible to occasional inundation, where a curtain of Pandanus can be found.

The five major vegetation entities are compared in Table 4. Belt transects were partitioned and assigned to one of the main vegetation classes. Frequency of each species in the vegetation class was determined by summing the number of one square meter quadrats which contained that species. As each vegetation class was represented by different numbers of samples, relative frequency was calculated for each species to facilitate comparison. This value is simply the percent calculated in the following way:

$$\text{Relative frequency} = \frac{\text{Frequency}}{\text{number of quadrats}} \times 100$$

Pandanus and the understory fern Phymatodes, were the only ubiquitous species found in all vegetation classes reflecting their ecological adaptability (Table 5). The coconut was by far the most commonly occurring species in the transects and it was an important component of all vegetation classes except the bog where the saturated substrate presumably excluded it all together. Of the other frequently occurring species Scirpus was confined to the bog and the Pandanus community which formed the transition from the bog to the closed forest. Asplenium, on the other hand, was restricted to the understory of the Coconut and Pisonia forest.

The vegetation types described in this work agree in general with those defined by Christophersen (1927), except in two instances. Christopherson did not recognize the forest dominated by Pisonia, perhaps because his interest focused on the bog community. Furthermore Christopherson did not mention the stands of breadfruit. This is not surprising since they are small in area and would not be easily found without the aid of aerial photographs.

Vegetation Communities

(1) Coconut Forest

Dense coconut forest covers perhaps eighty percent of

Table 4. Species composition of major vegetation types as measured by relative frequency*.

Species	Strand	Coconut Forest	Pisonia Forest	Pandanus Fringe	Bog
	Community Type				
Tournefortia argentea	35.5	0	4.1	0	0
Lepturus repens	35.5	0	0	0	0
Scaevola sericea	21.4	0	4.1	0	0
Canavalia carthartica	21.4	0	0	0	0
Cordia subcordata	7.1	0	0	0	0
Pipturus argenteus	7.1	1.0	2.0	0	0
Cocos nucifera	28.6	93.2	84.6	12.5	0
Phymatodes scolopendria	7.1	46.7	44.9	56.3	10.9
Pisonia grandis	0	0.5	51.0	0	0
Asplenium nidus	0	3.6	40.0	0	0
Morinda citrifolia	0	0	2.0	0	0
Pandanus tectorius	7.1	3.6	10.2	59.4	1.0
Nephrolepis exaltata	0	7.6	0	15.6	0
Psilotum nudum	0	0	0	0.5	0
Scirpus littoralis	0	0	0	21.9	92.1
Cyperus polystachyos	0	0	0	21.9	20.7
Cyrtosperma chamissonis	0	3.0	0	0	14.6
Number of quadrats	14	197	49	32	101

$$* \text{ Relative frequency} = \frac{\text{Frequency}}{\text{Number of quadrats}} \times 100$$

Table 5. Total frequency of occurrence of species in transects and number of vegetation types where species found

Species	Frequency*	Ubiquity#
Cocos nucifera	235	4
Phymatodes scolopendria	144	5
Scirpus littoralis	100	2
Asplenium nidus	99	2
Pandanus tectorius	33	5
Cyperus polystachyos	28	2
Pisonia grandis	26	2
Cyrtosperma chamissonis	21	2
Nephrolepis exaltata	20	2
Tournefortia argentea	7	2
Lepturus repens	5	1
Scaevola sericea	5	2
Pipturus argenteus	4	3
Canavalia carthartica	3	1
Psilotum nudum	1	1
Morinda citrifolia	1	1
Cordia subcordata	1	1

* Number of samples containing species

Number of major vegetation types where species occurs. Maximum possible value would be five where species occurred in all types viz. Strand, Coconut Forest, Pisonia Forest, Pandanus Fringe and Bog.

the land surface of Washington Island. The trees are tall and vigorous and regeneration is abundant. The understory is usually composed of Phymatodes or occasionally Asplenium or Nephrolepis. All these ferns grow both on the ground and as epiphytes. Phymatodes is more abundant in sunnier and more exposed sites. Nephrolepis also occurred widely but in much less abundance than the other two ferns. It typically grew as an ephiphyte in the closed forest. Immediately to the east of the village extensive areas of Cyrtosperma are cultivated in pits under the coconut canopy. Here the water table is close to the surface, and the base of the plants in their shallow pits, are submerged. The coconut in these circumstances grows on elevated patches and are surrounded by extensive pools of standing water which are presumably a human artifact. Coconut is not tolerant of truly saturated substrate, as was demonstrated by an unsuccessful attempt to plant them in the bog. Pandanus was occasionally encountered in the coconut forest but here its growth form has a tall spindly aspect as a result of competition for light with taller palms.

(2) Pisonia Forest

Although there are large tracts of forest where Pisonia is the conspicuous dominant, it is usually mixed with coconut to a greater or lesser degree. The largest stands are on the eastern end of the island where, in places, the trees are exposed to the prevailing winds and show the effect of wind shear. There is also a stand of extremely large trees about a mile from the western end of the island on the southern side and about a quarter of a mile from the shore. In the northwestern quarter of the island Pisonia is found mixed with coconut in greater amounts (Figure 6). Pisonia is most common on the raised outer rim of the atoll and is found on coral rubble or reefs of phosphate rock. In no case was it observed on the saturated substrate or peat.

Pisonia seemed to cast less dense shade than the coconut forest, which may explain why the understory of the community was more diverse. The most common understory plants were Phymatodes which occurred with about the same frequency as in the coconut forest and Asplenium, which was largely concentrated in the Pisonia forest (Table 4). However a number of low growing species such as Scaevola, Morinda, Tournefortia and Pipturus were encountered which were otherwise mainly associated with the strand vegetation which often lay adjacent to the Pisonia forest.

(3) Strand Communities

The strand vegetation around most of the island consisted of a thin band of Tournefortia mixed with Cocos, Cordia or Pandanus. Reflecting the more open character of the tree layer Scaevola was quite often present as an understory plant and Lepturus was encountered as a ground layer. Where there has been disturbance, such as around the village of Tengkore, at the site of the abandoned village of Manunu or at the location of old camps and the air strip, the strand species have acted as the colonizers. Scaevola, Pipturus,

Lepturus and the Canavalia and Ipomoea vines are abundant. On the western end of the island, a broad sand beach exists, there is an opportunity for Ipomoea and other extreme beach outpost species to gain a temporary foothold. Elsewhere wave action was typically found undercutting the shore such that high waterline usually lay under the canopy of the strand trees.

The outpost index of each species was calculated (Table 6) which is a measure of the tendency of species to act as extreme pioneer out on to the beach. Tournefortia had the greatest tendency and often its branches overhung the beach. Where beach sand was actively prograding herbaceous species such as Lepturus or Ipomoea were the extreme pioneers.

(4) Bog

The bog community is the simplest from the floristic point of view. Extensive areas are vegetated only with Scirpus which, at the time of our observations, was growing in water perhaps two or three centimeters deep. Others have noted that the bogs were dry (Judd, 1859; Christophersen, 1927) or covered with water to a depth of six to eighteen inches (Streets, 1877b). In places where the Scirpus was growing vigorously the substrate was firm. However in parts of the east bog the Scirpus had died in patches and only the dead root mat remained. Here the mud was soft and would not support the weight of a person. Around the margins of the bog, and in slightly elevated areas, Cyperus was found, sometimes growing in dense patches. On the remnants of mounds built in an attempt to establish coconut on the bog, colonies of Phymatodes and Cyrtosperma were found. Christophersen (1927) believed that the Cyrtosperma was invading into the bog. However there seems to have been no further advance in the fifty years since he was on the island and it would appear from his photographs that the Cyrtosperma is less vigorous now. A better explanation might be that these patches are relicts of former attempts to plant Cyrtosperma in the bog.

(5) Pandanus Fringe

In the narrow zone, often only a few meters wide, between the almost permanently saturated substrate of the bog and the raised land surface of the coconut forest, is a habitat in which the adaptable Pandanus dominates. The same community can be found in slightly raised islands within the bog, along the lake margin and adjacent the canals where material excavated from the canal was dumped.

The Pandanus in some places forms dense thickets and in others only scattered trees. In most instances sufficient sunlight penetrates to encourage low growing herbs such as Phymatodes, Nephrolepis, and Cyperus. Psilotum, may occasionally be found as an epiphyte.

(6) Scaevola - Tournefortia Scrub

Patches of dense scrub were found in a number of locations around the outer fringe of the island. In most instances they extended away from the beach a quarter of a mile inland. However they were also observed as islands

Table 6. Tendency of species to act as extreme pioneer on beaches as measured by outpost index*.

Species	Outpost index*
Tournefortia argentea	1.6
Lepturus repens	2.6
Ipomoea pes-caprae	2.6
Scaevola sericea	3.0
Portulaca oleracea	3.0
Laportea ruderalis	4.0
Pisonia grandis	4.3
Pandanus tectorius	5.0
Phymatodes scolopendria	5.4
Cordia subcordata	6.0
Cocos nucifera	6.3
Synedrella nodifera	6.5
Canavalia carthartica	8.0
Spermacoce assurgens	9.0
Asplenium nidus	9.4
Morinda citrifolia	10.1
Euphorbia hirta	11.0
Phyllanthus amarus	11.0
Cynodon dactylon	11.0
Cyperus polystachyos	11.0
Cyperus javanicus	11.5
Nephrolepis exaltata	13.3
Pipturus argenteus	15.0
Cyrtosperma chamissonis	18.0
Fimbristylis atollensis	19.0
Psilotum nudum	22.0
Scirpus littoralis	23.0

$$* \text{ Outpost index} = \frac{\text{Rank order of species from the sea}}{\text{Number of transects where species present}}$$

surrounded by coconut forest but never very far inland. They are conspicuous on aerial photographs and the outer road cuts through them in a number of places but they are so dense it was not feasible to penetrate far by foot. It appears that Scaevola forms dense thickets and is in places associated with Tournefortia parasitized by Cassytha. A similar community was encountered on Fanning Island landward from the shore on substrate of sand and coral rubble.

It is unclear why coconuts were not growing on these areas. It is possible that these may have been sites of guano digging although we have no independent evidence of this. The land may have been cleared of coconut and the substrate disturbed. The strand species would be the natural colonists of such disturbed sites and may have created a dense cover that the coconut has so far been unable to become established. The plantation managers attempted to make all possible land productive, and even went so far as to plant the bog which would seem to be a most inhospitable habitat for them. One would have thought that, even if the coconut could not colonize disturbed sites by themselves, they would have been planted artificially. The composition and physical environment of this community requires further investigation.

(7) Breadfruit Forest

On the northern flank of Tengkore is a patch of large Artocarpus (breadfruit) which are not tended and seem to be vigorous and reproducing. It is assumed that these are feral stands which have escaped from gardens where they were grown for food and wood. Another stand was found between the East and West Bogs completely surrounded by coconut forest but associated with an outcrop of phosphate rock but far from any present habitation. A small stand of bananas nearby suggests this might have been a former camp or satellite settlement especially since it is near the place where an old (but apparently not prehistoric) canoe was dug up in 1906.

Prehistoric vegetation

Four peat cores were taken in the bog (Figure 4, Table 1). They ranged in depth from 70 centimeters in the West Bog to 275 cm in the East Bog. The oldest deposit was from the base of the West Bog and was dated at 1060 $\pm$ 100 years BP. This would suggest that the peat facies slope downwards to wards the lake as would be expected. Pollen content from the peat was analyzed and is illustrated in Figure 9. The pollen concentration was extremely low throughout the core and all samples were dominated by grasses and sedges (mostly Scirpus) and fern spores which are produced in abundance in the immediate vicinity or the adjacent forest understory. Pollen from the Cocos, Pandanus, Pisonia and Tournefortia were present throughout the core but in very low numbers which might be expected from insect pollinated species. Although numbers are too small to allow any meaningful statistical analysis the results indicate no major vegetational change in the last millennium. The presence of Cocos throughout the core suggests that its importance in the

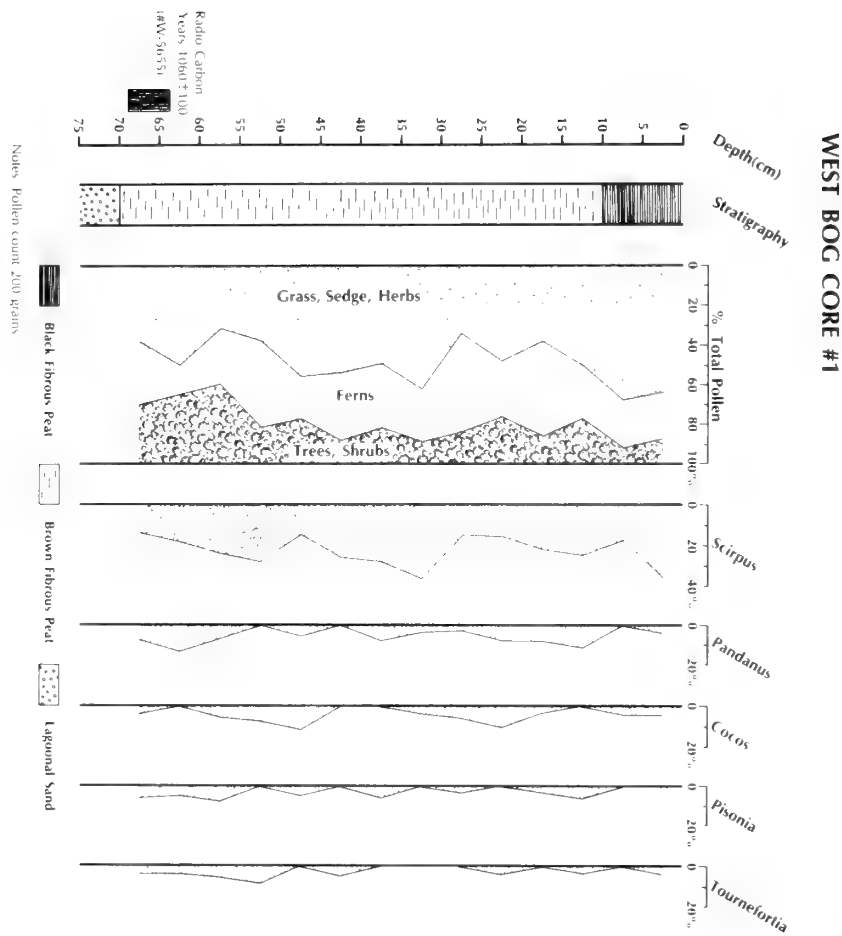


Figure 9. Pollen diagram

vegetation cover is of long standing. However as the core does not predate the period before Polynesian colonization which might be as early as 350 AD. If the coconut were a Polynesian introduction rather than an indigenous species its introduction resulted produced a profound change in the vegetation cover prior.

CONCLUSIONS

The earliest historical records of Washington Island, both from written descriptions and maps, indicate that almost all of the land surface was then dominated either by coconut or bog species. In essence this is what one would observe today despite 130 years of settlement, the construction of a village and camps as well as a road and canal system. In addition to the two main types of vegetation cover, natural ecotonal communities exist along the coast and at the transition between the coconut forest and the bog. Although the flora has been increased from 25 to 91 species, almost all the cultivated or adventive species are confined to disturbed areas around present or past settlements and along roadsides. However some food plants, such as breadfruit, babai and banana, persist in areas rarely visited today.

The record of the peat deposit suggests that the organic material accumulated rapidly and mostly in the last one thousand years during which time no environmental fluctualtion is evident. Coconut pollen was present throughout the core but, since the whole sedimentry sequence postdates possible Polynesian occupation, it does not shed light on the role of prehistoric navigators in spreading the coconut through the Pacific.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Martin Vitousek for his assistance in making all the arrangements to visit Washington Island, Mote Teraoi for his hospitality on the island, and also Dr. Meyer Ruben of the United States Geological Survey for providing carbon dates for peat samples.

BIBLIOGRAPHY

Anonymous, 1874-86, Pacific Islands: Arundel, Plant Lists, Tropical Asia, Australasia and Southern Islands, 1874-86, Volume 14, bound volume of determination lists in Royal Botanical Gardens, Kew.

-------, 1958, How Abbe Rougier got his coconut empire, Pacific Islands Monthly, August 1958, pp. 84-5, 99.

Anderson, Thelma and Marion Kelly, 1980, More on Fanning's William Greig, Pacific Islands Monthly, June 1980.

Arundel, John T. 1870-1919, Diaries, Pacific Manuscript Bureau Docs. 480-492.

-------1890, Phoenix Group and other islands of the Pacific. New Zealand Herald, 5 and 12 July, Auckland.

Ball, S. C. n.d. Field note books, manuscript in the library of the Bernice P. Bishop Museum.

Becke, Louis, 1897, Wild life in the Southern Seas, T. Fisher, London.

Behm, E. von, 1859, Das Amerikanische Polynesien, Petermanns Mittheilungen, 1859. pp. 173-194.

Bellwood, Peter, 1979, Man's conquest of the Pacific, Oxford University Press, New York.

Bennett, Frederick D., 1970, Narrative of a whaling voyage round the globe from the year 1833 to 1836, 2. vols., N. Isreal, Amsterdam and Da Capo, New York, facsimile of 1840 edition published by Richard Bentley, London.

Bloxham, Andrew, 1925, Diary 1824-24, Bernice P. Bishop Museum, Special Publication 10.

Brown, F.B.H., 1930, New Polynesian Plants, Occasional Papers Bernice P. Bishop Museum, 9:1-23.

--------, 1931, Flora of southeastern Polynesia, Bulletin Bernice P. Bishop Museum, 84.

Bruner, Philip L., 1972, Field guide to the birds of French Polynesia, Pacific Scientific Information Center, Bernice P. Bishop Museum, Honolulu.

Bryan, Edwin H. Jr. 1942, American Polynesia and the Hawaiian chain, Tongg Publishing Co., Honolulu.

------- 1974, Panala'au memoirs, Bernice P. Bishop Museum, Honolulu.

Carter, John (Ed.), 1984, Pacific Islands yearbook, Pacific Publications, Sydney.

Chock, Alvin, 1963, J. F. Rock, 1884-1962, Taxon, 12:89-102.

------- and Dean C. Hamilton, 1962, Plants of Christmas Island, Atoll Research Bulletin, 90.

Cumberland, Kenneth B., 1956, Southwest Pacific; A geography of Australia, New Zealand and their Pacific Island neighbors, MaGraw Hill, New York.

Christophersen, Erling, 1927, Vegetation of Pacific equatorial islands Bulletin Bernice P. Bishop Museum, 44.

Dawson, E. Yale, 1959, Changes in Palmyra Atoll and its vegetation through the agency of man, 1913-1958, Pacific Naturalist, 1:1-51.

Edmondson, Charles H. 1923, Crustacea from Palmyra and Fanning Islands, Bulletin Bernice P. Bishop Museum, 5.

Emory, Kenneth P., 1934, Archeology of the Pacific equatorial islands, Bulletin Bernice P. Bishop Museum, 123.

------- 1939, Additional notes on the archaeology of Fanning Island, Occasional Papers Bernice P. Bishop Museum, 15:179-189.

English, H. 1857, Letter to William Miller, H.B.M. Consul general in the Pacific Ocean. Foreign Office Record 58/85, pp. 507-508.

Elschner, Carl, 1915, The Leeward Islands of the Hawaiian Group, Sunday Advertiser, Honolulu, 68pp.

-------, 1922, Kolloide phosphate, Kolloid Zeitshcrift 31:94-96.

-------, 1923, Beitrage zur kenntnis der koralleninseln des Stillen Ozeans, Zeitschrift fur Praktische Geologie, 31:69-73.

Fanning, Edmund., 1970, Voyages around the world, Gregg Press, Upper Saddle River New Jersey. Facsimile of original edition published by Collins and Hannay, New York, in 1833.

Findlay, Alexander George, 1884, A directory for the navigation of the South Pacific Ocean, 5th edition, Richard Holmes Laurie, London.

Finney, Ben, 1958, Recent finds from Washington and Fanning Islands, Journal of the Polynesian Society, 67:70-72.

Finsch, O., 1868, Die Papageien, 2 vols., E.J. Brill, Leiden.

Fosberg, F. R. 1939, Notes on Polynesian grasses , Occasional Papers Bernice P. Bishop Museum,15:37-48.

-------, 1943, Notes on the plants of the Pacific atolls III, a brief summary, Bulletin Torrey Botanical Club, 70:386-397.

-------, 1953, Vegetation of Central Pacific atolls, a brief summary, Atoll Research Bulletin, 23.

-------, 1954, Soils of the northern Marshall atolls, with special reference to the Jermo Series, Soil Science, 78:99-107.

-------, 1957, Description and occurrence of atoll phosphate rock in Micronesia, American Journal of Science, 225:215-232.

-------, 1962, The Natural History Society (Christmas Island) and its Bulletin, Atoll Research Bulletin, 94:1-5.

Fuller, G., 1903, Report on Fanning Island, typescript in the archives of Unilever Ltd., London.

Gallagher, M. D., 1960, Bird notes from Christmas Island, Pacific Ocean, The Ibis, 102:489-502.

Gardner, 1833, Log of the Bowditch, Pacific Manuscript Bureau Doc. 833.

Garnett, Martin, 1981, Christmas Island wildlife sanctury: Information to visitors, Wildlife Conservation Unit, Christmas Island, mimeo.

Geesink, R., 1969, An account of the genus Portulaca Indo-Australia and the Pacific, Blumea, 17:275-301.

Greene, Daniel B., 1860-65, Log of the Massachusetts, Pacific Manuscript Bureau Doc. 349.

Gregory, Herbert E., 1923, The report of the Director for 1923, Bulletin Bernice P. Bishop Museum, 4.

-------, 1925, The report of the Director for 1924, Bulletin Bernice P. Bishop Museum, 24.

-------, 1935, The report of the Director for 1934, Bulletin Bernice P. Bishop Museum, 133.

Haggerty, J. A., 1982, The geology of the Southern Line Islands, Ph.D. dissertation, Department of Geology and Geophysics, University of Hawaii.

Hemsley, William Botting, 1855, List of the plants collected in the Pacific Islands by J.T.Arundel, Report on the scientific results of the voyage of the H.M.S. Challenger. Botany Vol. 1, Part 4, p. 116.

Herms, William B., 1925, Entomological observations on Fanning and Washington Islands, together with general biological notes, Pan-Pacific Entomologist, 2:49-54.

------- 1926, Diocalandra taitensis (Guerin) and other coconut pests of Fanning and Washington Islands, Philippine Journal Science, 30:243-271.

Holley, Richard, 1853-57, Log of the Washington, Pacific Manuscript Bureau Doc. 369.

Holtum, R.E., 1974, Asplenium Linn. sect. Thamnopteris, Gardener'sBulletin, 27:143-154.

Hudson, William L., 1840, Log of the Peacock, Pacific Manuscript Bureau Docs. 773 and 370.

Hutchinson, G. E., 1950 Biochemistry of vertebrate excretion, Bulletin of American Museum of Natural History, 96.

Jackson, E. O. and S. O. Schlanger, 1976, Regional synthesis, Line Islands Chain, Tuamotu Island Chain and Manahiki Plateau, Central Pacific Ocean. In: S. O. Schlanger and E. O. Jackson et al., Initial Report, Deep Sea Drilling Project, Vol. 33, pp. 915-927, U.S. Government Drilling Project, Washington D.C.

Jenkin, R.N. and M.A. Foale, 1968, An investigation of the coconut-growing potential of Christmas Island, 2 vols., Ministry of Overseas Development, Directorate of Overseas Surveys, Land Resource Study No. 4.

Judd, Gerrit Parmele, 1859, Journal of G. P. Judd. Manuscript in the library of the Hawaii Misssion Children's Library, Honolulu.

Keyte, G.S., 1861, Fanning's Island: An incident, The Friend, 18:31.

Kirch, P.V. 1984, The evolution of Polynesian chiefdoms, Cambridge University Press, Cambridge.

Kondo, Y. and Willian J. Clench, 1952, Charles Montague Cooke Jr.: A bio-bibliography, Special Publication, Bernice P. Bishop Museum, 42.

Langdon, Robert, 1974, Arundel, the shy Cecil Rhodes of the Pacific Islands, Pacific Islands Monthly, 45:59-61.

-------, 1978, American Whalers and Traders in the Pacific; A guide to microfilm records, Australian National University, Canberra.

Lucett, Edward, 1851, Rovings in the Pacific from 1837 to 1849, 2 vols. Longman, Brown, Green and Longmans, London.

Loomis, Maria, 1819-24, Journal of Mrs. Maria Sartwell Loomis, Hawaii Mission Children's Library, Honolulu, Hawaii.

Loomis, Elisha, 1820-24, Journal of Elisha Loomis, Hawaii Mission Children's Library, Honolulu, Hawaii.

Loumala, Katherine, 1953, Ethnobotany of the Gilbert Islands, Bulletin Bernice P. Bishop Museum, 213,

Mottler, Lee S., 1986, Pacific Island names, Miscellaneous Publication Bernice P. Bishop Museum, 34.

Nelson, S. G. and F. A. Cushing Jr., 1982, Survey of the brackish lake in Pulusuk with regard to its potential for fish culture, University of Guam, Technical Report No.77.

Northrop, John, 1962, Geophysical observations on Christmas Island Atoll Research Bulletin, 89:1-2.

McClellan, Edwin North, 1940, The American island of Washington, Paradise of the Pacific, 52(5):19, 24.

Maragos, James E., 1979, Palmyra Atoll: Preliminary environmental survey and assessment, U.S. Army Corps of Engineers, Honolulu.

Martelli, V., 1926, A new species of Pandanus from Fanning Island, University of California Publications in Botany,13:145-146.

Merrill, E.D., 1925, On the flora of Fanning and Washington Islands, Christophersen referred to this manuscript when preparing his study of the vegetation of the Central Pacific atolls and stated that it was on file in the Library of the Bernice P. Bishop Museum. No trace can be found of it there.

Miller, William, 1857, Letter to William Miller, Her Britanic Majesty's Consul General in the Pacific Ocean, Foreign Office Papers 58/85, Miller's No. 14. A copy of this correspondence is in the Kuykendall papers in the University of Hawaii Library.

Ministry of Education Training and Culture, Kiribati Government, 1979, Kiribati: Aspects of history, published jointly with Pacific Studies and Extension Services, University of the South Pacific, Tarawa, Kiribati.

Neal, Marie C., 1965, In gardens of Hawaii, Bernice P. Bishop Museum Press, Honolulu.

New York Tribune, 1858, March 5th.

Oliver, James, 1848, Wreck of the Glide, Wiley and Putnum, London.

Palmer, P.D.F. 1956, Hugh Greig obituary, Archives Burns Philp Company, University of Sydney.

------- 1973, Correspondence and typed copy of 1861/2 log kept by Fanning Island settlers, Archives Burns Philp Company, University of Sydney.

Ploenitz, Karl von, 1936, New species of Portulaca from Southeastern Polynesia, Occasional Papers, Bernice P. Bishop Museum, 12:1-6.

Powers, F.D., 1925, Phosphate deposits of the Pacific, Economic Geology, 20:266-281.

Preston, R. S., E. Person and E. S. Deevey, 1955, Yale Natural radiocarbon measurements II, Science, 122:954-960.

Restarick, Henry Bond, 1929a, Names of old Honolulu families found in Fanning Island history, Honolulu Star-Bulletin, September 7th.

-------, 1929b, Raid on Fanning Island in 1914 by German gunboat Honolulu Star-Bulletin, September 14th.

-------, 1929c, Many ships in olden days crashed to destruction on Fanning Islands, Honolulu Star-Bulletin, September 21st.

Republic of Kiribati, 1983, Resources study of Fanning and Washington, Ministry of Natural Resources and Development, Tarawa.

Rock, Joseph F., 1916, Palmyra Island: with a description of its flora, Honolulu Star Bulletin, Honolulu.

-------, 1929, The voyage of the Luka to Palmyra Island, Atlantic Monthly, 144:360-366.

Sachet, M-H., 1962, Geography and land ecology of Clipperton Island, Atoll Research Bulletin No. 86.

Schlanger, S. O. and I. Premoli Silva, 1981, Tectonic, volcanic and paleogeographic implications or redeposited reef faunas of late Cretaceous and Tertiary age from the Narau Basin and the Line Islands In: Initial reports of the deep sea drilling project, Volume 61, pp. 817-828, U.S. Government Printing Office, Washington D.C.

Sclater, P.L., 1876, Report on Pacific parrot, Coriphilus kuhli, Proceedings Royal Zoological Society, London, 1876:420-421.

Sharp, Andrew, 1956, Ancient voyagers in the Pacific, Polynesian Society Memoir No. 32, Polynesian Society, Wellington, New Zealand.

-------, 1963, Ancient voyagers of Polynesia, Angus and Robertson, Sydney.

Sinoto, A., 1973, Fanning Island: Preliminary archaeological investigations of sites near the Cable Station, In: Fanning Island Expedition, July and August, 1972, Final Report, Hawaii Institute of Geophysics Technical Report 73-13, pp. 283-299.

Skerrett, Joseph S., 1873-4, Log of the U.S.S. Portsmouth, manuscript in the U.S. National Archives, Washington D.C.

Sledge, W. A. 1984, University of Leeds, personal communication.

Spriggs, M., 1980, Early coconut remains from the South Pacific, Journal of the Polynesian Society, 93:71-76.

Stanton, William, 1975, The great United States exploring expedition, of 1838-42, University of California Press, Berkeley.

Stokes, John F. G., n.d. Archeological notes on Washington Island. Manuscript in the Bernice P. Bishop Museum Library.

Stone, Benjamin C., 1968, Notes on Pandanus in the Line Islands, Micronesica, 4:85-93.

St. John, Harold, 1952, A new variety of Pandanus and a new species of Fimbristylis from the Central Pacific Islands. Pacific Plant Studies 11, Pacific Science, 6:145-150.

-------, 1974, The vascular flora of Fanning Island, Line Islands, Pacific Ocean, Pacific Science, 28:339-355.

Stimson, J. F. and D. S. Marshall, 1964, A dictionary of some Tuamotuan dialects of the Polynesian language, Martinus Nijholl, The Hague.

Stoddard, David R. and T.P. Scoffin n.d. (1983), Phosphate rocks on coral reef islands, In A. S. Gouldie and Kenneth Pye (Eds.) Chemical sediments and geomorphology, Academic Press, London.

Streets, Thomas H., 1876, Description of a new duck from Washington Island, Bulletin Nuttall Ornitholigical Club, 1:46-47.

-------, 1977a, Contributions to the natural history of the Hawaiian and Fanning Islands and Lower California made in connection with the U.S. North Pacific Surveying Expedition 1873-75, Bulletin of the U.S. National Museum, 7.

-------, 1877b, Some account of the natural history of the Fanning group of islands, American Naturalist, 11:65-72.

Tennant, B. S. and N. Mutter, 1977, Economic survey of the Northern Line Islands, Gilbert Islands, London.

Taylor, Ronald C. 1973, An atlas of Pacific Island rainfall, Hawaii Institute of Geophysics Data Report, 25 (Technical Report 73-9).

Unilever, Ltd., 1903, Fanning and Washington Islands, papers including a description of the islands and correspondence regarding their ownership. in the library of Unilever Ltd. London.

United States Congress, 1859, An act to authorize protection to be given to citizens of the United States who may discover deposits of guano, Statutes at Large, Vol. 11, 34th. Congress, Session 1. pp. 119-120.

Updike, John, 1973, Pigeon feathers and other stories, Knopf, New York.

Vitousek, Martin J., Bernard Kilonsky and Wayne G. Leslie, 1980, Meteorological observations in the Line Islands 1972-80, Hawaii Institute of Geophysics Data Report 38, (Technical Report 80-7).

Ward, R.G and B.J. Allen, 1980, The viability of floating coconuts. Science in New Guinea, 7:69-72.

Wentworth, Chester K. 1925, A tropical peat bog, Bulletin Geological Society of America, 36:137.

-------, 1931, Geology of the Pacific equatorial islands, Occasional Papers Bernice P. Bishop Museum, 11.

Wester. Lyndon, 1985, Checklist of the vascular plants of the Northern Line Islands, Atoll Research Bulletin 287.

Whistler, Arthur, 1983, A flora and vegetation of Swains Island, Atoll Research Bulletin, No. 262.

Wilkes, Charles, 1970, Narrative of the U. S. Exploring xpedition, 5 vols., Gregg Press, Upper Saddle River, New Jersey, (facsimile of first edition published in 1845).

Weins, A, 1962, Atoll environment and ecology, Yale University Press, New Haven and London.

Yen, Douglas, n.d. Notation on accession card Bernice P. Bishop Museum.

ATOLL RESEARCH BULLETIN

NO. 359

STUDIES OF SOILS AND PLANTS IN THE NORTHERN MARSHALL ISLANDS

BY

S.P. GESSEL AND R.B. WALKER

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

CONTENTS

ACKNOWLEDGEMENTS

The authors were associated in Marshall Island investigations from 1958-1964 with many individuals who contributed to the information reported in this document. These included University of Washington faculty associates, graduate students, and special investigators. Also, substantial field assistance was rendered by Marshallese residents. In the case of the students, some of the work has been reported in theses but in many instances the source was field or laboratory notebooks. We particularly wish to acknowledge the contributions of the following individuals:

Dr. Lauren Donaldson, Director of the University of Washington Laboratory of Radiation Biology at the time of the original studies.

Dr. Edward E. Held, Leader of the expeditions.

Dr. Ralph Palumbo (deceased), Botanist in the Laboratory of Radiation Biology

Graduate students on the project:

Dr. Mark Behan
Richard Billings
Dr. Dale Cole
Dr. Wallace Gentle (deceased)
Theodore Hoffman (deceased)
Reid Kenady
James Kimmel
Dr. Gyorgi Léskó
Dr. Richard Miller
Richard Rolla
Dr. John Severson
Dr. Carole Tocher
Toshiaki Yamashita

Consultant:

James Nishitani

In February, 1986, we observed the atoll soils and vegetation again under the auspices of the Lawrence Livermore Laboratory (Dr. William Robison, leader of the field party). This gave the opportunity to check and supplement earlier observations. We also thank Professor Earl L. Stone, who was also a member of the 1986 field party, for his valuable suggestions for improvement of an earlier version of the manuscript.

The authors however assume full responsibility for the contents of this paper.

LIST OF FIGURES

LIST OF TABLES

STUDIES OF SOILS AND PLANTS IN THE NORTHERN MARSHALL ISLANDS

BY

STANLEY P. GESSEL[1] AND RICHARD B. WALKER[2]

INTRODUCTION

During the period 1958-1964, the authors undertook soil and vegetation studies in the northern Marshall Islands as part of the University of Washington Radiation Biology Laboratory surveillance team. This team was responsible for monitoring levels of radiation in various components of the island environment and any effects on plant and animal life. The authors of this report were charged with the soils and vegetation components but assisted with collections in the aquatic ecosystems and some food plant materials. Collections and measurements were made during relatively short term visits to the islands with sample processing and analysis performed during intervening periods. Much of the field and laboratory work was done by graduate students in the College of Forest Resources and the Department of Botany, with results reported in theses, but generally not in the open press. Therefore, we use some of this material in the report, together with unpublished material from our files.

The emphasis of field collection of both soils and plants was to establish levels of radiation across the range of island environments and exposure levels and to monitor these over time. For this reason, sampling points were generally marked for return collections. This made possible a variety of studies of the soils and plants, which are presented in this paper. Effort was initially expended on an inventory of soils and plant associations on the islands so that these could form a basis for sampling. All identified soil series were sampled throughout the profiles and chemical and physical analysis made. Special collections were made to study distribution of radionuclides, and lysimeters were used to study movement of nuclides as well as major cations and anions. Plant and litter samples were studied to assess absorption and cycling of mineral elements, with special emphasis on ^{137}Cs. Because ground water is important on some of the islands the ground water lens was also sampled to the extent feasible.

---

[1]College of Forest Resources, University of Washington, Seattle, Washington 98195, U.S.A.

[2]Department of Botany, University of Washington, Seattle, Washington 98195, U.S.A.

Manuscript received 12 October 1991; revised 25 November 1991

Much of the material and information collected had not been published because of the termination of contracts with the University of Washington. The authors were given the opportunity to revisit some of the collection sites on Bikini and Rongelap Atolls in 1986 and reinventory some of the older work. This led to the decision to make the material available for other researchers. Although we were never able to carry out complete ecosystem studies, we believe that what we present will be of current interest, and useful in any future investigations.

For orientation, a map of the Northern Marshall Islands is included (Figure 1), as well as more detailed maps of the atolls on which observations were made: Rongelap (Figure 2), Bikini (Figure 3) and Enewetak (Figure 4). Also to aid readers with respect to atoll plants, a list of the common plant species is included (Table 1). Identification of plants was made using Taylor (1950) and Baker (1959).

SOILS: GENERAL DESCRIPTION AND METHODS

General Characteristics. Soils of Pacific atolls on which these studies took place are dominated by the environment in which they have developed and by the parent materials. They have originated from the detritus of corals and other marine life cast slightly above high tide, and then stabilized by plants. Consequently, mineral materials, so common in continental land masses, are absent from these atoll soils, except for small amounts of pumice. Topographic variations are slight so that factors of drainage, erosion and mass earth movements play only a minor role in the subsequent course of soil development. The nature of the materials and soil development has been described by Fosberg and Carroll (1965) and Porter (1966). Also Morrison (1990) has recently discussed the chemical properties, mineralogy, and classification of atoll soils with a few comments on the northern Marshall Islands.

The marine origin of the soils means that they are dominated by carbonate parent materials, largely calcium carbonate, but magnesium carbonate also plays a role. This original marine detritus must change in order to be a hospitable substrate for plant growth and plant community development. Certain essential elements have to be added to the soil system, and the development and maturity of the soil in this island system seem to be largely functions of such additions. Studies on Rongelap, Bikini and Enewetak atolls indicate that accumulation of nitrogen plays a major role in the maturation and general improvement of soils. Fresh marine debris, largely coralline in nature, has little nitrogen, but in this warm, humid environment, nitrogen fixation and accumulation is rapid, far exceeding that found in temperate regions. Therefore, in terms of nitrogen status, a soil can change from rather sterile lime sand to a reasonably fertile substrate within a matter of ten to twenty years.

As a result of these various influences on soils, any given atoll is likely to have soils of several ages, fertility, and productivity on the different islands. Some of the small islets give the appearance of having just emerged from a salt water environment, and

Table 1. More Common Plants Found in the Northern Marshall Islands[a].

Species	Family	Habitat Notes
Tree Form		
Bruguiera conjugata	*Rhizophoraceae*	Tidal or wet areas
Cocos nucifera	*Palmaceae*	Village areas; plantations
Cordia subcordata	*Boraginaceae*	Occurs in thickets; poorer soils
Neisosperma oppositifolia (formerly Ochrosia parviflora)	*Apocynaceae*	Wooded central areas
Pandanus sp.	*Pandanaceae*	Widely distributed over islands
Pisonia grandis	*Nyctaginaceae*	Good soils in island centers
Soulamea amara	*Simarubaceae*	Scattered trees
Terminalia litoralis	*Combretaceae*	Scattered behind beach or shore rocks
Tournefortia argentea (formerly Messerschmidia)	*Boraginaceae*	Disturbed soil; wide occurrence
Tree-Like to Shrubby		
Dodonaea viscosa	*Sapindaceae*	Thickets in disturbed areas
Guettarda speciosa	*Rubiaceae*	Very common; beaches to interior
Morinda citrifolia	*Rubiaceae*	Near villages and coconut plantations
Pemphis acidula	*Lythraceae*	Behind fringe vegetation; in rocky intertidal areas
Pluchea odorata	*Compositae*	In disturbed areas near villages
Scaevola frutescens (= S. sericea)	*Goodeniaceae*	Very abundant; forms fringe vegetation at beaches and thickets over many areas
Suriana maritima	*Surianaceae*	On windward beaches
Tournefortia argentea	*Boraginaceae*	Disturbed soil; common
Shrubs		
Clerodendron inerme	*Verbenaceae*	Near settlements or coconut plantations
Pseuderanthemum atropurpureum	*Acanthaceae*	Village areas
Sida fallax	*Malvaceae*	Clumps near coconut groves
Understory Plants		
Boerhaavia spp.	*Nyctaginaceae*	Often under Pisonia; shaded areas; variable soil
Portulaca spp.	*Portulacaceae*	Poorer soil; in the open
Tacca leontopetaloides	*Taccaceae*	Good soil under coconuts
Triumfetta procumbens	*Tiliaceae*	Spreading stoloniferous cover; open areas; beaches
Vines		
Ipomea alba (= I. macrantha)	*Convolvulaceae*	Spreading vine in many areas; disturbed sites
Cassytha filiformus	*Lauraceae*	Parasitic; vine-like over other plants
Canavalia microcarpa	*Leguminosae*	Spreading under coconuts

Table 1, continued.

Species	Family	Habitat Notes
Grass; Grass-like		
Cenchrus echinatus	Poaceae	Village areas; plantations
Chloris inflata	Poaceae	Coconut areas
Eleusine indica	Poaceae	Shade of coconuts
Eragrostis amabilis	Poaceae	Woodland glades
Fimbristylis cymosa	Cyperaceae	On poorer areas
Lepturus repens	Poaceae	Poorer disturbed areas
Thuarea involuta	Poaceae	Shaded, wooded areas
Ornamental-Food		
Artocarpus altilis	*Urticaceae*	Trees in village areas
Carica papaya	*Caricaceae*	Village areas
Cocos nucifera	*Palmaceae*	Plantations; village areas; otherwise scattered groves
Crinum asiaticum	*Amaryllidaceae*	Settled areas; cemeteries
Hibiscus tiliaceus	*Malvaceae*	In villages
Plumeria rubra	*Apocynaceae*	Village areas

[a] Botanical names follow Taylor (1950); with some modifications from Fosberg (1988)

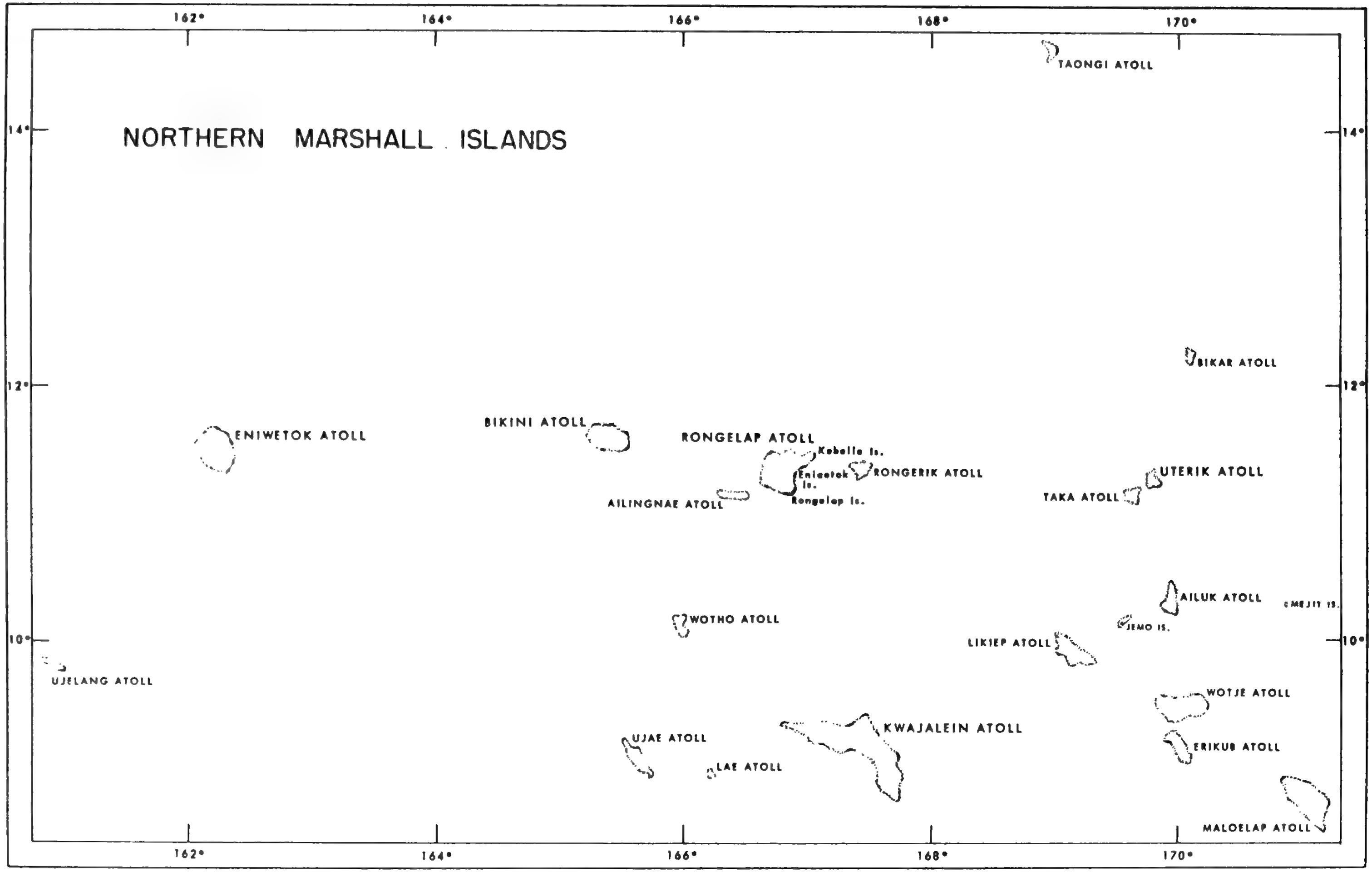


Figure 1. Map of the Northern Marshall Islands

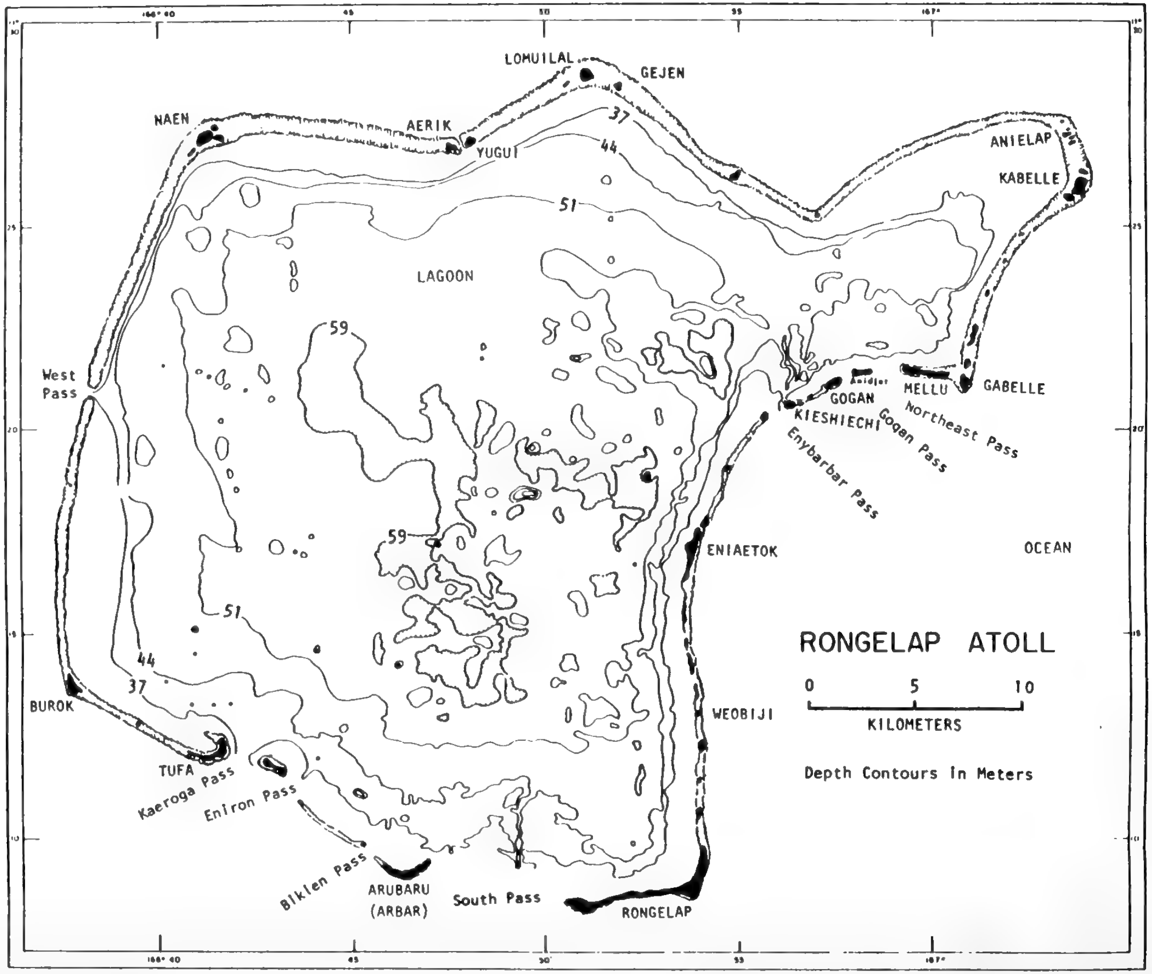


Figure 2. Map of Rongelap Atoll

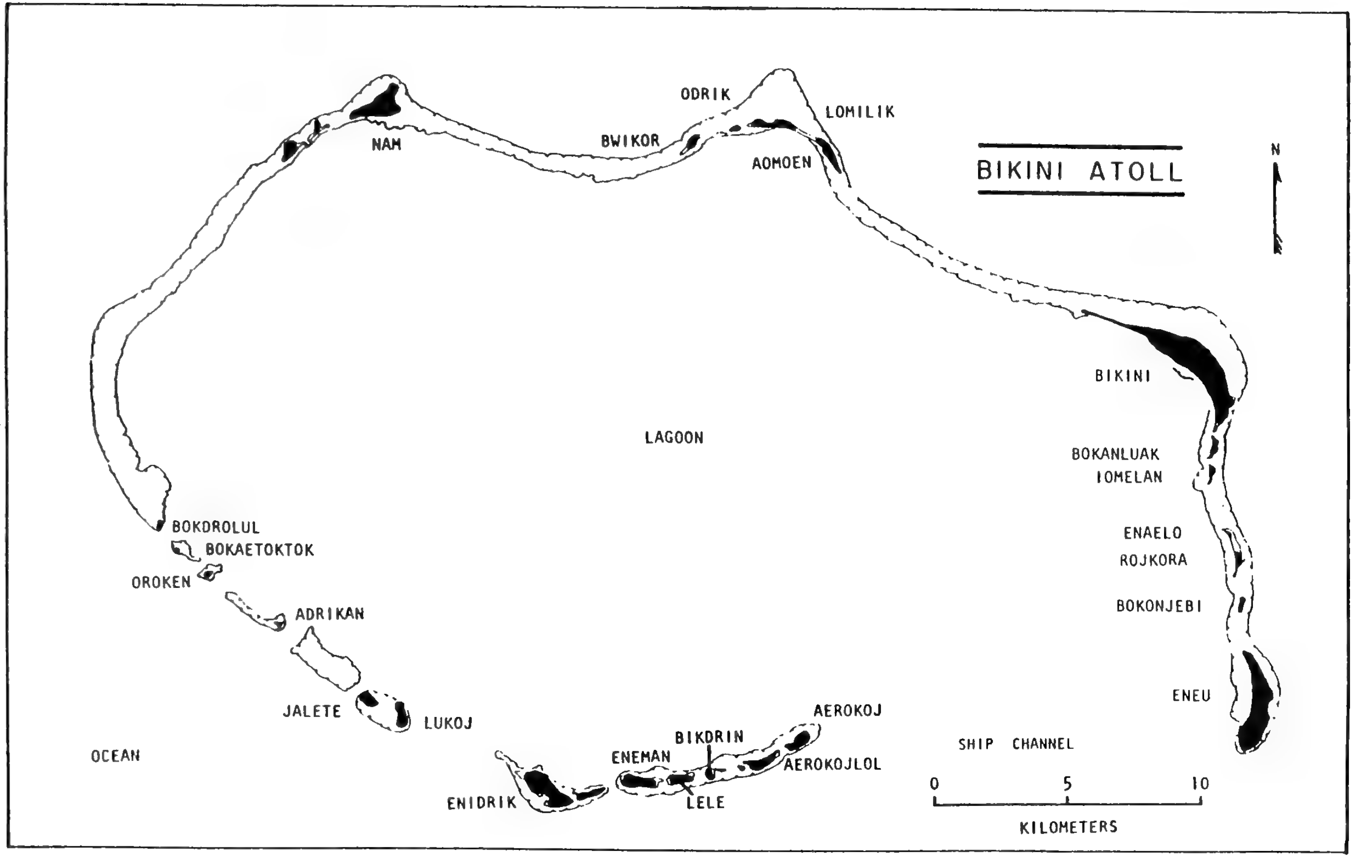


Figure 3. Map of Bikini Atoll

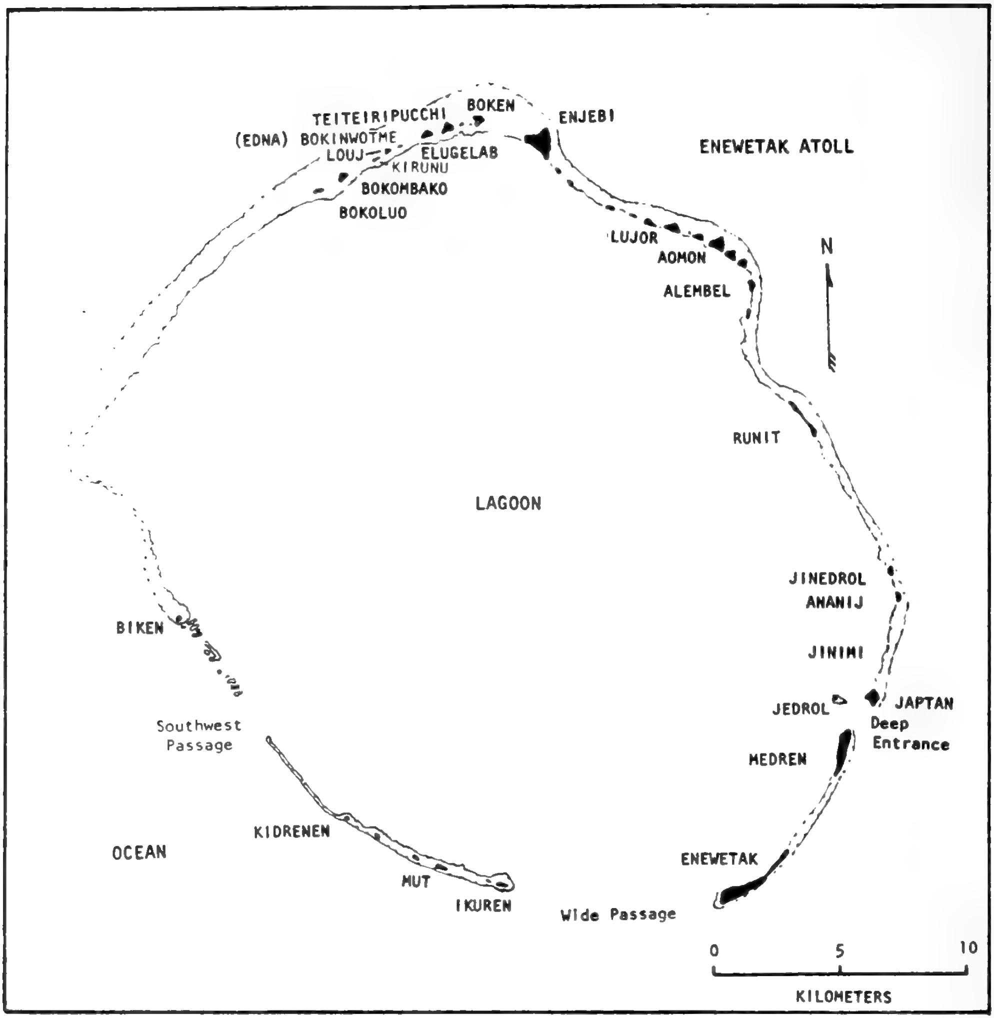


Figure 4. Map of Enewetak Atoll

vegetation and soil development is at an early stage. Larger islands, particularly if they are more than a few hundred meters wide, have areas of very well developed and fertile soils. These more mature soils are high in organic matter, nitrogen, and phosphorus to a depth of 30 to 45 cm. Native vegetation is lush on these soils, and many such areas have been cleared for coconut production. They contrast with the white coral sands of young soil areas of either the same or adjacent islands. Foliage color, as well as chemical composition of the plants, is related to the general state of development and organic matter accumulation of the soil.

Our evidence also shows that certain other elements, particularly those needed only in small amounts, such as iron, zinc and manganese, are at critically low levels even for native plant growth. Factors which tend to concentrate or add these elements to the system therefore become important to the development of fertile soils.

The invasion and succession of plants in the island environment also relates to soil development. Some of the plants have an ability to grow in sea water or in only small dilutions of sea water. These plants can extract elements from the sea and place them into a cycle which is part of the land mass life cycle. Similarly, certain sea birds which nest in island vegetation can contribute. They carry small fish to their young, and through residues from this feeding operation, as well as from the excrement of the total population, large quantities of elements necessary for plant growth are introduced. Kenady (1962) quoted an estimate of 2 metric tons/ha/yr of guano for Kabelle Island on Rongelap Atoll. Again our evidence suggests that major additions of nitrogen, phosphorus, zinc, manganese, copper and other elements occur in this manner.

There are certain destructive forces acting in this environment which have an impact on both vegetation and soil. Repeated visits to certain islands over a period of a few years have shown definite changes in shorelines and beach areas. Over long periods of time major storms have entirely covered most of the islands at some time with salt water and new marine detritus. Evidence in deep soil pits suggest that this process has been repeated many times (see Fig. 10), even in the northern Marshalls, which have typhoons less frequently than do atolls farther south. Well developed buried A_1 soil horizons have been found as deep as 200 cm (80 inches) below the surface of existing stable land areas. All atolls and islets we have investigated show evidence of periodic inundation. This fits in with the observations that major island features in the atolls are formed or destroyed by typhoons (Fosberg and Carroll, 1965).

Soil Sampling

Sampling procedures provided for taking appropriate types of soil samples for radionuclide status, nutritional level, series characterization, and bulk density. At selected locations, a standardized set of soil samples was taken within a 15x15 cm area and at 2.5 cm depth increments. At some locations samples were taken in duplicate as well as different depth sequences. All material within this volume was placed in plastic containers for transport to the ship laboratory. It was oven dried at 105°C and then shipped to Seattle. Eventually, the samples were re-dried at 105°C, sieved through a 2

mm sieve, and both components weighed. Bulk densities were calculated from the volume and weight data. The fine portion passing the 2 mm sieve was further pulverized and then used for radionuclide determination, as well as elemental analyses. Radionuclide analysis of some of the coarse fractions was also made. After soil series were mapped, a type soil pit was established in each series and all horizons were sampled (Kenady 1962). Plant materials were collected and plant growth conditions recorded at all pit sites.

Soil cores, using a 7.6 cm diameter metal tube approximately 30 cm long and machined with sharp cutting edges, were also taken. A lead brick was used to drive the tubes into the soil. Snug fitting wooden plugs were then sealed at each end of the tube and the entire unit was shipped to the Seattle laboratory. Upon arrival these were oven dried, weighed, and impregnated with plastic according to the method described by Held et al. (1965b). The cores were used for studies of radionuclide distribution, as well as to study soil profile characteristics.

Ground water was sampled by driving a well point of our own design into the water lens wherever possible. Each of these consisted of a length of pipe of interior diameter 1.25 cm, with the point itself a perforated section. Water was extracted from the lens, when encountered, by Tygon tubing evacuated with a hand pump. One to two liters of water were generally collected. At many sample points near shores, it was impossible to contact the water lens because of beach rock layers.

Soil Analyses

For pH determination, subsamples were taken from the bulk samples before drying, then measured in the field laboratory on a 1:1 soil to distilled water ratio using a battery operated glass electrode pH meter.

For all other analyses the bulk samples were oven-dried, then seived through a 2 mm screen. The percentage by weight of material larger than 2 mm is reported in the tables of analyses. In each case, organic material which did not pass through the 2 mm screen was ground in a steel mortar, then combined with the other material which had passed through the 2 mm screen to make up the sample used for nitrogen, phosphorus and exchangeable cation analyses.

Total nitrogen was determined by the Kjeldahl method as described by Jackson (1958). Phosphorus was extracted and determined colorimetrically by the bicarbonate method of Olsen et al. (1954). Exchangeable cations were extracted with ammonium acetate, then determined with a Beckman DU flame photometer. Exchange capacity was measured on the same sample by displacing the adsorbed ammonium with sodium chloride, then distilling and titrating the ammonia (Jackson, 1958).

Organic matter content was determined by difference. The amount of calcium carbonate was calculated from the volume of carbon dioxide given off when the sample was mixed with hydrochloric acid in a closed system. This calculated weight of calcium

carbonate was then subtracted from the oven dry weight of the sample to approximate the weight of organic matter present, since no detectable silica was in the samples. Some error is introduced by the presence of some magnesium carbonate, which on a unit weight basis would release more carbon dioxide than calcium carbonate, thus making the calculated organic matter values lower than the true amount. However, if magnesium carbonate is in the range of 10% of the total carbonate as might be expected, this error will not be large.

The total analyses of soils as in Tables 10 and 17 were made by heating samples with 6N HCl, which dissolved all carbonate material and intensively extracted the organic matter. Analyses were made on suitable aliquots of the filtrate from this digest by the following methods: Ca, Mg by EDTA titration; K, Na by flame photometry; B by the curcumin method (Dible et al., 1954); Zn and Cu by the zincon method after anion exchange separation (Sandell, 1959); Mn by the tetrabase method (Sandell, 1959); and Fe by the thiocyanate method (Sandell, 1959).

RONGELAP ATOLL SOILS

Characteristics of Soil Series

In order to provide a basis for systematically sampling soils and making comparisons, the soils of Rongelap and Kabelle Islands were investigated thoroughly in early visits and a soil mapping system developed. This is described by Kenady (1962) in detail. Names assigned to soils identified as definitive units (series) will be used in this report. Similar soil units were recognized on Enewetak and Bikini Atolls in 1964. Summary information on the principal soil series is presented in Tables 2 through 6 along with photographs of typical soil profiles and micromonoliths in Figures 7 through 11, adapted from Kenady (1962). Locations of the soil pits referred to in these figures are given on the maps of the Northeastern part of Rongelap Island (Figure 5) and the map of Kabelle Island (Figure 6). For specific geographic location, the benchmark (BM) in Figure 5 is at latitude 11°8'88" N. and longitude 166°53'35" E. Although Stone (1951, 1953) and Fosberg (1954) had done some studies on northern Marshall Atoll soils and had established some series names, these did not seem to fit the soils we were observing. However our Gogan series may be a younger stage of the Jemo series described by Stone on Arno Atoll in the southern Marshall Islands (1951) and by Fosberg (1954) for the northern Marshall atolls, and referred to recently by Fosberg (1990) and Morrison (1990). Fosberg and Carroll (1965) have a more complete discussion of atoll soils, but done after our studies. For these reasons we will use names originally given to soils based on detailed chemical and physical analyses (see next section).

The data of Tables 2-6 give a general characterization of the soil series. However some caution is advisable in considering the data. In many instances, the sum of the exchangeable cations exceeds the measured exchange capacity. We believe that some dissolution of solid phase carbonates by the ammonium acetate leaching solution can explain these overruns.

Table 2. Characteristics of Rongelap Gravelly Sand, Representative Profile, Pit 22, Rongelap Island

	Sample Depth—cm						
Property	0-12.5	12.5-30.5	30.5-46	46-66	66-91	91-127	127-168
Percent Material > 2mm	46	50	39	**	28	39	54
Percent Nitrogen	0.99	0.53	0.11	**	0.03	0.02	0.02
Percent Organic Matter	26.5	12.6	4.5	2.6	2.6	1.2	1.9
Exchange Capacity	34.1	12.3	6.3	3.1	0.8	**	**
*Sodium	3.47	1.48	0.91	0.55	0.64	**	**
*Magnesium	4.95	1.59	1.00	0.78	0.70	**	**
*Calcium	**	**	2.95	2.00	1.45	**	**
*Potassium	1.61	0.65	0.30	0.17	0.16	**	**
Phosphorus (ppm)***	85	45	26	6.4	15	5.1	7.1
pH	8.0	8.0	8.1	8.6	8.6	8.8	8.7

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 3. Characteristics of Gogan Gravelly Sandy Loam, Representative Profile, Pit 4, Kabelle Island

	Sample Depth—cm					
Property	***	0-2.5	2.5-12.5	12.5-30	30-50	50-65
Percent Material > 2mm	10	20	20	27	39	56
Percent Nitrogen	1.54	1.96	0.42	0.18	0.07	0.05
Percent Organic Matter	21.4		5.9	6.8	2.6	2.6
*Exchange Capacity	20.5	43.6	17.9	7.2	2.6	1.7
*Sodium	2.0	3.0	0.8	0.4	0.4	0.4
*Magnesium	7.0	7.4	4.0	2.2	1.2	1.1
*Calcium	10.3	**	14.1	6.2	7.7	7.8
*Potassium	**	**	**	**	**	**
Phosphorus (ppm)****	1330	893	416	216	151	25
pH	7.4	7.1	7.9	8.2	8.6	8.8

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Organic layer above mineral soil
**** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 4. Characteristics of Lomuilal Sand, Representative Profile, Pit 8, Rongelap Island

	Sample Depth—cm				
Property	0-7.5	7.5-25	25-30	30-52.5	52.5-120
Percent Material > 2mm	0	5	18	12	2
Percent Nitrogen	0.29	0.07	0.08	0.04	0.02
Percent Organic Matter	2.8	2.3	2.2	1.9	1.7
*Exchange Capacity	14.2	2.3	2.6	1.1	0.6
*Sodium	2.73	0.73	0.82	0.82	0.84
*Magnesium	4.66	0.84	1.05	0.85	0.83
*Calcium	5.02	1.87	2.50	2.31	2.35
*Potassium	1.09	0.18	0.19	0.16	0.16
Phosphorus (ppm)***	106	15.1	14.1	5.0	5.0
pH	8.4	8.6	8.3	8.8	9.1

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 5. Characteristics of Beach Ridge Sand, Representative Profile, Pit 2, Rongelap Island

	Sample Depth—cm							
Property	0-5	5-12.5	12.5-22.5	22.5-30	30-45	45-92.5	92.5-110	110+
Percent Material > 2mm	8	16	10	12	32	7	14	21
Percent Nitrogen	0.08	0.13	0.07	0.15	0.09	0.03	0.03	0.01
Percent Organic Matter	3.8	3.9	3.2	5.3	3.7	1.9	1.3	1.1
*Exchange Capacity	2.8	4.6	2.1	7.0	2.4	0.8	1.0	0.1
*Sodium	1.29	1.06	0.85	1.96	1.31	1.09	1.06	1.28
*Magnesium	2.07	2.61	2.49	1.51	1.21	1.67	1.51	1.51
*Calcium	2.63	3.48	2.26	3.50	3.13	2.76	2.81	2.63
*Potassium	0.39	0.50	0.23	0.38	0.26	0.23	0.18	0.21
Phosphorus** (ppm)	18.1	14.1	10.0	10.1	8.0	9.0	26.0	10.0
pH	8.4	8.4	8.6	8.3	8.5		9.0	8.5

* Exchangeable cations in meq per 100 grams of oven dry soil (2mm fraction)
** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 6. Characteristics of Kabelle Sand, Representative Profile, Pit 6, Kabelle Island

	Sample Depth—cm		
Property	0-2.5	2.5-27.5	27.5-95
Percent Material > 2 mm	34	8	2
Percent Nitrogen	0.22	0.02	0.01
Percent Organic Matter	8.1	**	2.6
*Exchange Capacity	6.3	0.3	0.1
*Sodium	1.57	3.01	1.37
*Magnesium	1.37	1.04	1.16
*Calcium	3.01	2.88	2.65
*Potassium	0.57	0.15	0.20
Phosphorus (ppm)***	30.0	12.0	12.0
pH	8.9	9.1	9.2

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Analysis not available
*** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 7. Bulk Density of Soil Cores from Enewetak, Bikini, and Rongelap Atolls (1964).

Core No.	Location	Island	Bulk density g/ml
1	Disturbed area	Runit	1.30
2	Native vegetation	Biken	1.04
3	Disturbed area	Bokombako	1.21
4	Disturbed area	Bokombako	1.27
5	Coconut stand near airfield	Eneu	0.84
6	Open *Scaevola* near airfield	Eneu	1.08
7	*Pandanus*; island center	Bikini	0.92
8	*Scaevola* seaward	Bikini	1.17
9	Under *Guettarda*	Bikini	1.33
10	Seaward reef area	Bikini (Reef)	1.15
11	Near crater	Aomoen	1.14
12	Near crater	Bwikor	1.31
13	*Tournefortia*	Nam	1.18
14	Crater area	Nam	1.06
15	Undisturbed area	Bokdrolul	1.31
16	Crater area	Eneman	1.12
17	*Tournefortia*	Bikdrin	1.20
18	Disturbed dock area	Aerokoj	1.20
19	*Pisonia* area	Kabelle	1.01
20	Open area	Bokinwotme	1.28
21	*Tournefortia*	Bokinwotme	1.21

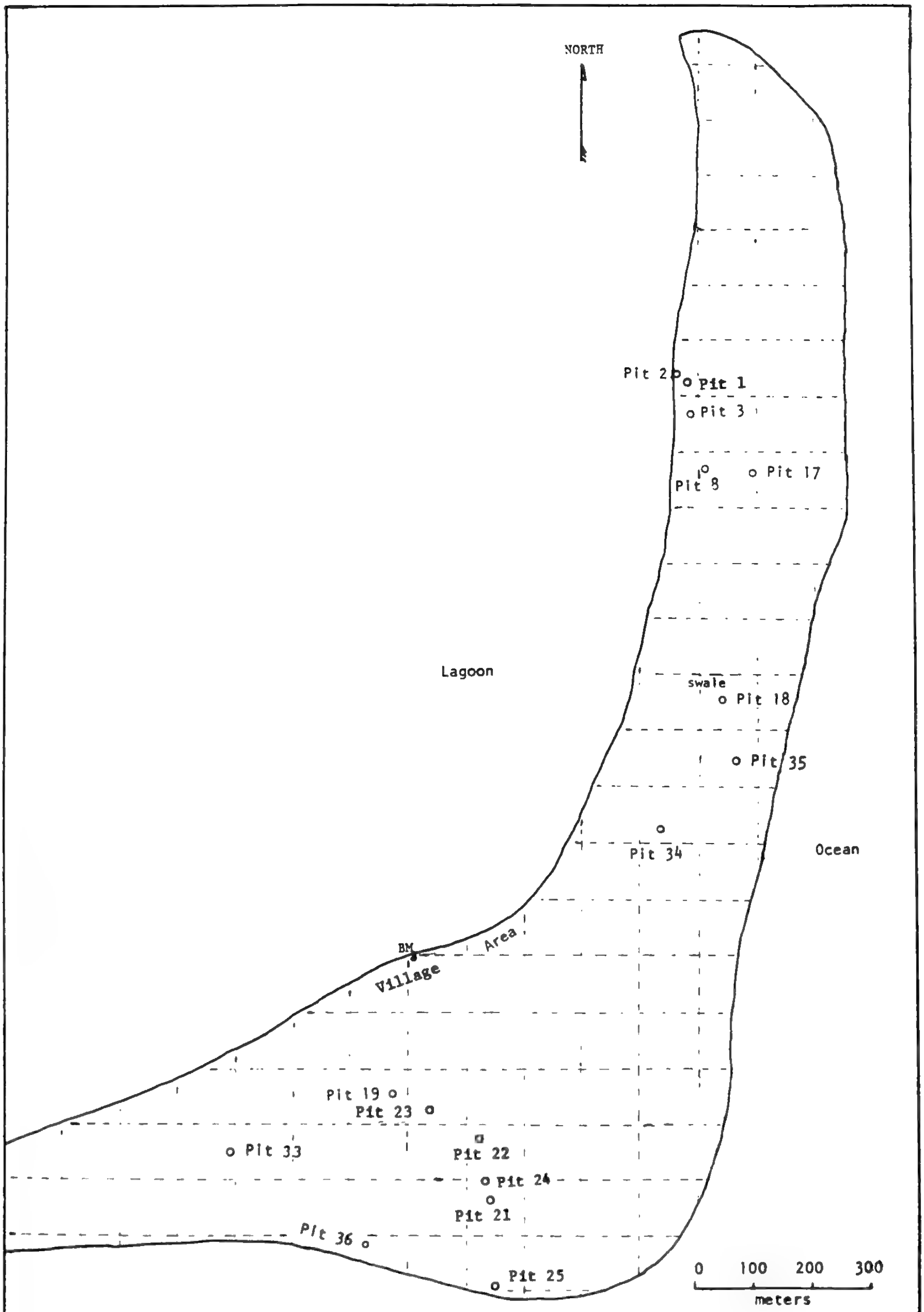


Figure 5. Map of the Northeastern Part of Rongelap Island, Showing Locations of soil Pits.

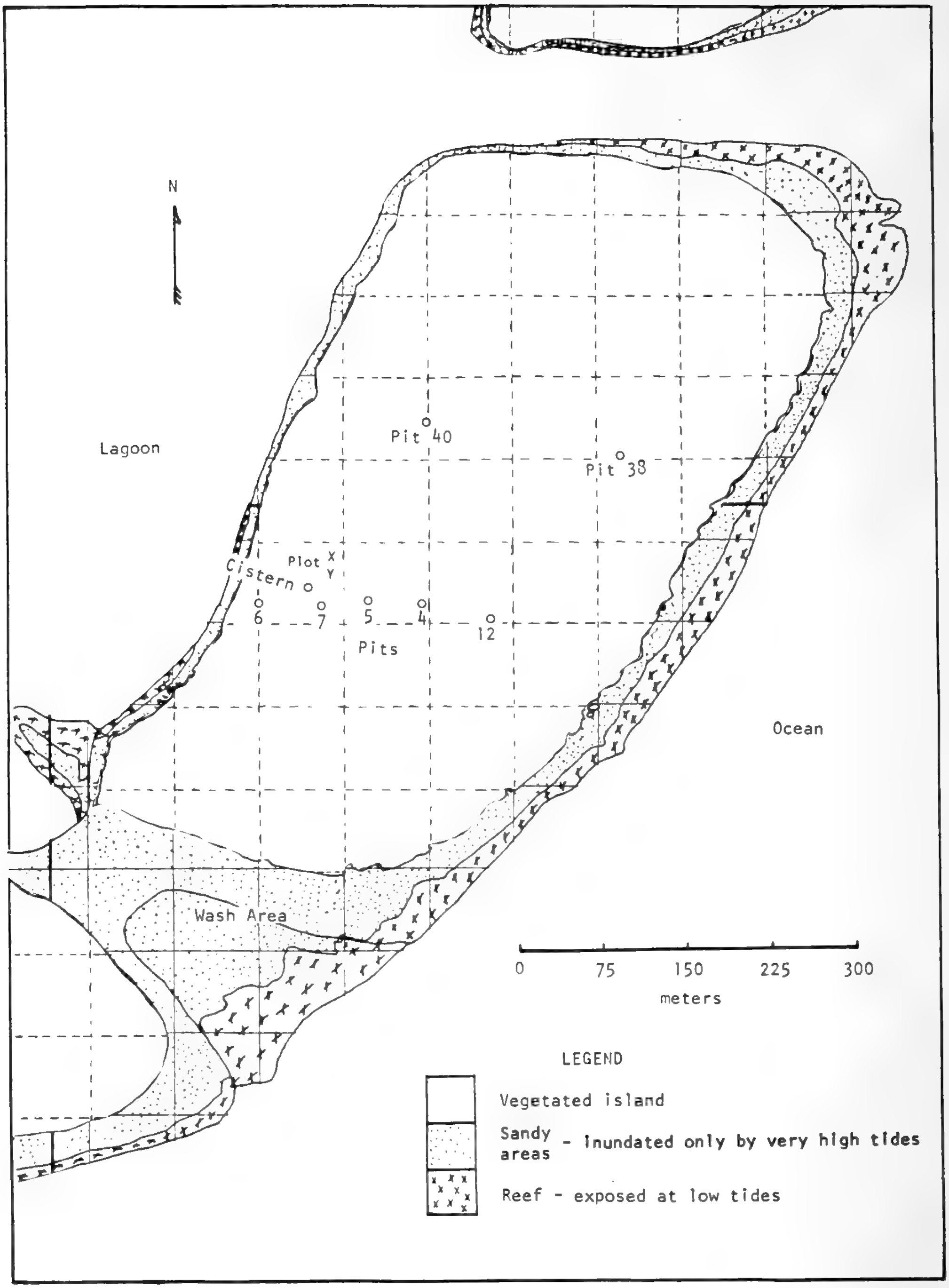
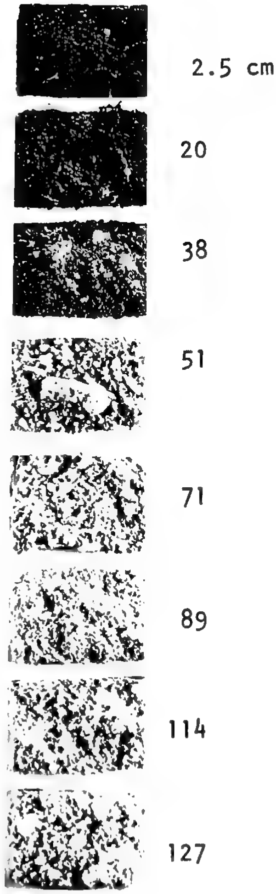


Figure 6. Map of Kabelle Island, Rongelap Atoll, Showing Locations of Soil Pits

Pit 7 under coconut trees on Kabelle Island, with Triumfetta growing below and the compound-leafed Tacca above.

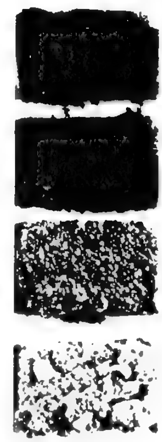


Micromonolith, Pit 22 on Rongelap Island

Coconut grove near Pit 22

Figure 7 Rongelap Gravelly Sand: Typical profile and vegetation

Pit 4 on Kabelle Island, under Pisonia trees, with Boerhaavia ground cover. Note the well point for obtaining ground water.



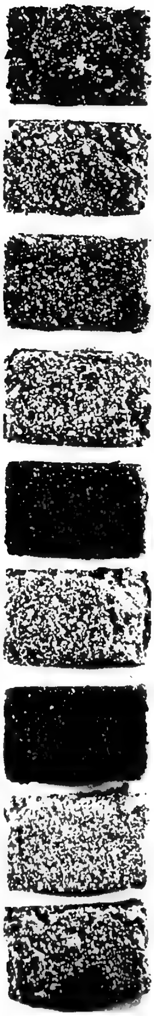
Micromonolith of Pit 38

Stand of Pisonia grandis in the Pit 38 area, Kabelle Island

Figure 8 Gogan Series: Typical profile and vegetation

Pit 12 on Kabelle Island
(Dark strata are buried horizons)

Tournefortia argentea near Pit 12
(Boerhaavia spp. cover the ground)



2.5 cm
13
25
38
94
112
130
142
152

Micromonolith
of Pit 21 on
Rongelap Island

Figure 9 Lomuilal Sand: Typical profile and vegetation

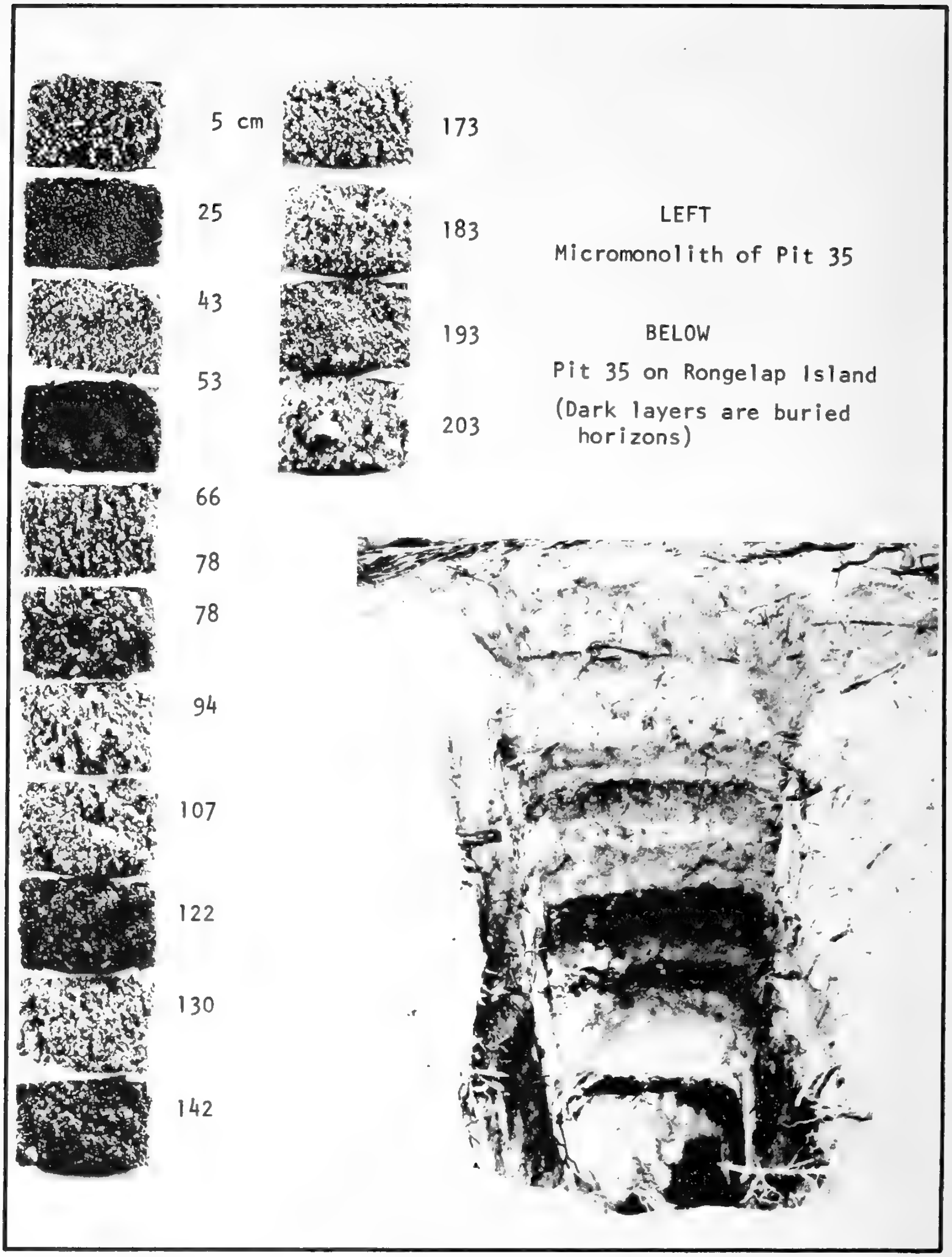
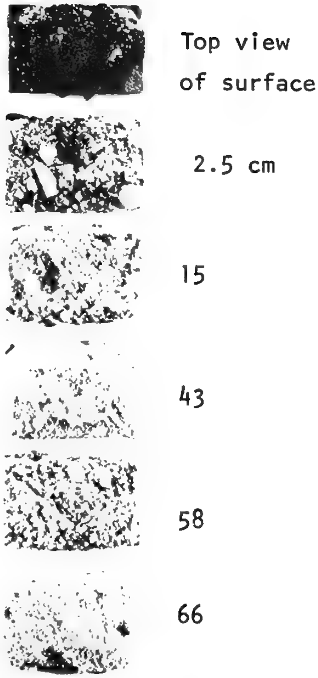


Figure 10 Beach Ridge Sand: Typical profile with buried horizons

Soil Pit 6 on Kabelle Island. The black areas are crusts formed by algae.



Micromonolith of Pit 6

View of the Pit 6 area, with its shrubby open strand vegetation.

Figure 11 Kabelle Sand: Profile and vegetation

Significance of Series Separations

The five principal soil series were examined by analysis of variance to test for the significance between levels of nitrogen, organic matter, exchange capacity and soil reaction. These levels were means from three replicate samples of A_1 horizons. Table 8 shows the basic data for these comparisons.

Of the four factors studied, differences in total nitrogen and exchange capacity were statistically significant at the 0.1 percent level, organic matter was significant at the 1.0 percent level, and pH was nonsignificant. These results indicate that based on essential chemical properties, the soil series are distinct and separate units and that sampling based on these units was reasonable for the studies.

Other Data

A great deal of information on gravel content of the soils and bulk density is given in the theses of Kenady (1962) and Billings (1964) and more exists in unpublished files (available from the authors). Typical bulk densities from the 30 cm soil cores are in Table 7. Bulk densities of the surface 2-3 cm are lower, typically about 0.5 g/ml. During the various expeditions to Rongelap from 1958 to 1964 some of the established soils pits used to represent the soil series, and study radionuclide deposition and movement, were sampled in 2.5 cm increments to a depth of 37.5 cm. In most cases the sampling was in duplicate. A September 1963 sampling of this kind was also used for a complete chemical analysis. Because these data could be of interest in plant growth and nutrition studies they are presented in Table 10. Pits 4 and 38 are in the interior of Kabelle Island under the influence of Pisonia trees and sea birds. Pits 1 and 22 are under coconut plantings on Rongelap Island and these soils are used for island food production. Pit 6 is a young soil on the lagoon beach of Kabelle Island under vegetation struggling to become established. The wash area samples are essentially new deposits of sand, occasionally washed by sea water. Nitrogen and phosphorus distribution in the profiles clearly reflects the seabird contributions and organic matter accumulation. Calcium and magnesium show the coral origin of the soils but also the dilution by organic matter and weathering. There is considerable variation in the elements in some of the profiles, some of which is due to buried horizons or other depositional features. The micro-element data are more limited but show low levels of manganese through all soils and low levels of iron, zinc, and copper in the young and emerging soils. Also considerable data was published on the behavior of the soil solution from tension lysimeter studies (Cole et al. 1961), with the most noteworthy feature being the pronounced stimulation of leaching of all ions by fertilizer additions of nitrogen or potassium.

Plant-Soil Interrelationships on Rongelap Atoll

The single source of soil parent material, the few plant species and associations, and the distinctive age groupings of soils and plants allowed for soil and vegetation sampling over an age range. Single individuals or specific stands of the dominant plant species were selected on what we judged to be young or more mature soils. On a

Table 8. Nutrient Levels and Soil Reaction in the A_1 Horizon of the Five Most Extensive Soil Series

Soils Series	Rongelap Gravelly Sand	Gogan Gravelly Sandy Loam	Lomuilal Sand	Beach Ridge Sand	Kabelle Sand
Percent Nitrogen	0.57	1.71	0.26	0.09	0.14
Percent Organic Matter	16.7	35.6	6.4	4.5	7.7
*Exchange Capacity	22.2	37.7	12.6	3.7	5.7
*Sodium	3.36	4.01	2.68	1.16	1.52
*Magnesium	4.19	11.1	3.21	2.55	1.92
*Potassium	1.95	1.80	0.79	0.37	0.46
Phosphorus (ppm)**	81.7	985	54.2	32.8	32.1
pH	8.1	7.8	8.4	8.6	8.6

* Exchangeable cations in meq per 100 grams of oven dry soil (2 mm fraction)
** Phosphorus extracted by bicarbonate (Olsen et al., 1954)

Table 9. Dry Weight and Nitrogen Content of Vegetation Litter, Rongelap Atoll

Area	Year	Species	No. Samples	Litter Weight*		Nitrogen*	
				g/m^2	kg/ha	g/m^2	kg/ha
Various islands of the Atoll	1961	*Tournefortia Guettarda Scaevola*	11	1,074	10,740	6.7	67
Wash. Area Plots Kabelle	1961	*Tournefortia Guettarda Scaevola*	19	1,343	13,430	7.3	73
Weobiji	1961	*Pisonia*	9	1,185	11,850	21.6	216
Weobiji	1962	*Pisonia*	20	981	9,810	17.8	178
Pit 6-Kabelle	1963	*Pisonia*	20	1,614	16,140	20.7	207
Rongelap Isl.	1964	*Pisonia*	20	1,904	19,040	45.3	453
Rongelap Isl.	1961	*Scaevola*	1	587	5,870	4.4	44
Rongelap Isl.	1961	*Tournefortia*	1	1,001	10,010	6.7	67
Pit 38-Kabelle	1961	*Scaevola*	1	1,000	10,000	7.5	75
Pit 38-Kabelle	1961	*Tournefortia*	2	1,114	11,140	7.5	75
Pit 38-Kabelle	1961	*Tournefortia*	1	1,549	15,490	14.7	147
Pit 38-Kabelle	1961	*Scaevola*	1	839	8,390	6.3	63

* Mean values

Table 10. Elemental Composition[1] of Contrasting Rongelap Atoll Soil Profiles

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
			Nitrogen—Percent			
0.0 - 1.25	1.21	3.58	4.71	0.80	0.15	0.04
1.25 - 2.5	0.69	1.88	4.78	0.62	0.03	0.03
2.5 - 5.0	0.43	0.60	4.61	0.59	0.03	0.02
5.0 - 7.5	0.31	0.38	1.73	0.42	0.02	0.02
7.5 - 10.0	0.19	0.37	0.43	0.34	0.02	0.02
10.0 - 12.5	0.25	0.29	0.25	0.26	0.02	0.02
12.5 - 15.0	0.20	0.22	0.18	0.25	0.02	0.02
15.0 - 17.5	0.17	0.22	0.18	0.21	0.02	0.02
17.5 - 20.0	0.21	0.21	0.21	0.15	0.02	0.01
20.0 - 22.5	0.31	0.19	0.20	0.14	0.02	
22.5 - 25.0	0.15	0.18	0.17	0.12	0.02	
25.0 - 27.5	0.12	0.13	0.17	0.10	0.02	
27.5 - 30.0	0.10	0.14	0.14	--	0.02	
30.0 - 32.5	0.09	0.12	0.11	0.09	0.02	
32.0 - 35.0	0.08	0.10	0.13	0.09	0.02	
35.0 - 37.5	0.07	0.08	0.10	0.08	0.02	
			Phosphorus—ppm			
0.0 - 1.25	2912	5187	6060	5394	409	394
1.25 - 2.5	2156	3842	2000	5248	348	392
2.5 - 5.0	2006	2543	1776	4890	298	370
5.0 - 7.5	1087	1719	6575	4295	33	388
7.5 - 10.0	967	1524	5939	4072	270	327
10.0 - 12.5	1062	1165	3430	3785	315	363
12.5 - 15.0	1006	925	3600	1910	349	333
15.0 - 17.5	859	950	3275	3879	335	312
17.5 - 20.0	822	875	624	4152	360	
20.0 - 22.5	1250	731	2124	4781	312	
22.5 - 25.0	603	625	2188	4030	266	
25.0 - 27.5	862	830	1876	--	300	
27.5 - 30.0	375	830	848	3394	315	
30.0 - 32.5	443	631	1336	--	290	
32.5 - 35.0	381	449	1351	2790	275	
35.0 - 37.5	379	506	1212	2921	248	
			Calcium—Percent			
0.0 - 1.25	14.2	8.9	4.6	33.1	26.7	
1.25 - 2.5	22.9	17.4	3.0	35.1	35.5	
2.5 - 5.0	18.8	32.0	3.0	35.9	37.7	
5.0 - 7.5	16.0	17.8	18.3	--	41.6	
7.5 - 10.0	27.2	26.6	26.2	35.7	39.5	
10.0 - 12.5	22.8	35.3	24.5	35.6	41.5	
12.5 - 15.0	31.7	25.7	29.5	35.9	38.2	
15.0 - 17.5	25.4	40.4	37.5	34.2	39.6	
17.5 - 20.0	27.9	16.3	15.9	33.1	46.3	

Table 10. continued.

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
			Calcium—Percent			
20.0 - 22.5	29.4	32.9	21.4	36.7	26.0	
22.5 - 25.0		15.1	20.3	40.1	37.6	
25.0 - 27.5		36.1	26.7	--	24.5	
27.5 - 30.0		33.7	--	37.0	42.1	
30.0 - 32.5		19.1	24.8	--	29.0	
32.5 - 37.0		31.8	26.9	37.8	37.4	
37.0 - 37.5		31.9	31.4	40.1	--	
			Magnesium—Percent			
0.0 - 1.25		5.59	0.71	4.44	6.79	
1.25 - 2.5	0.23	6.51	1.57	1.22	3.32	
2.5 - 5.0	1.08	1.17	0.49	2.00	3.06	
5.0 - 7.5	0.49	7.38	1.34	--	3.01	
7.5 - 10.0	0.39	2.38	0.93	2.40	2.35	
10.0 - 12.5	1.62	2.04	1.82	1.59	3.24	
12.5 - 15.0		2.87	1.31	4.34	4.32	
15.0 - 17.5	0.62	2.24	0.39	5.12	3.71	
17.5 - 20.0	0.08	--	1.16	3.07	1.87	
20.0 - 22.5		5.11	0.39	7.29	5.59	
22.5 - 25.0		3.67	1.08	1.44	0.62	
25.0 - 27.5		3.72	1.85	--	2.84	
27.5 - 30.0		6.67	0.62	1.47	3.30	
30.0 - 32.5		7.26	2.55	--	5.33	
32.5 - 35.0		2.18	3.43	2.13	3.20	
35.0 - 37.5		1.19	2.55	1.49	--	
			Iron—ppm			
0.0 - 1.25	100	40	170	65	18	
1.25 - 2.5	68	38	115	--	10	
2.5 - 5.0	26	36	125	39	1.3	
5.0 - 7.5	30	33	140	19	1.3	
7.5 - 10.0	31	26	55	15	2.5	
10.0 - 12.5	45	43	38	15	7.5	
12.5 - 15.0	35	24		15	7.5	
15.0 - 17.5	35	30		30	7.5	

Table 10, continued.

Depth cm	Pit 1	Pit 4	Pit 38	Pit 22	Pit 6	Wash Area Kabelle Is.
			Manganese—ppm			
0.0 - 1.25	1.56	0.52	0.18	1.56	0.03	0.41
1.25 - 2.5	1.75	0.44	0.50	0.94	0.12	0.22
2.5 - 5.0	1.00	0.75	0.31	1.11	0.18	0.35
5.0 - 7.5	1.03	0.78	0.18	0.65	0.21	0.29
7.5 - 10.0	0.87	0.72	0.06	0.75	0.18	0.20
10.0 - 12.5	0.66	0.25	0.12	0.81	0.12	0.28
12.5 - 15.0	0.37	0.22	0.25	1.04	0.12	0.37
15.0 - 17.5	1.15	0.31	0.38	1.22	0.10	0.49
17.5 - 20.0	0.87	0.03	0.00	0.65	0.38	0.39
20.0 - 22.5	3.00	0.18	0.50	0.40	0.21	
22.5 - 25.0	0.68	0.00	0.50	0.38	0.08	
25.0 - 27.5	0.10	0.00	1.44	--	0.38	
27.5 - 30.0	0.15	0.00	0.00	0.25	0.06	
30.0 - 32.5	0.20	0.00	0.88	--	0.06	
32.5 - 35.0	0.11	0.00	0.44	0.18	0.12	
35.0 - 37.5	0.20	0.00	0.31	0.06	0.25	

Other elements

	Pit 38		Pit 22		Pit 6	
Depth cm	Zn	Cu	Zn	Cu	Zn	Cu
0.00 - 1.25	145	23	10	27	9	32
1.25 - 2.5	47.5	24	--	34	3	
2.5 - 5.0	95	21	7	27	0	
5.0 - 7.5	--	--	--	--	2	
7.5 - 10.0	8.3	6	34	0	-	
10.0 - 12.5	5.3	--	5	28	2	
12.5 - 15.0	1.5	0	2	24	3	
15.0 - 17.5	4.5	--	8	23	0	
17.5 - 20.0	4.0	21	7	22	-	
20.0 - 22.5	--	27	52	26	0	
22.5 - 25.0	2.5	21			6	
25.0 - 27.5	1.5	24			0	
27.5 - 30.0	0.0	22			2	
30.0 - 32.5	2.0	19			2	
32.5 - 35.0	1.0	21			1	
35.5 - 37.5	1.5	20			2	

[1] Nitrogen by Kjeldahl. Other elements based on HCl digest (see p. 11 for Methods).

specific area basis, collections were made of current litter, humus layers if they existed, and soils at three depth increments to a total depth of 30 cm. At some isolated locations, litter trays were also set out, with litterfall collections at each visit to the area. Information from these collections has not been presented previously so detailed summary tables are given in this report along with short discussions of the data.

Litterfall and Litter Decomposition

Weight and nitrogen contribution of litter from the principal plant species are given in Tables 9 and 13. The species seem to produce about the same amount of litter as associations, or as individual shrubs, with ranges between 1000 to 1500 g/m^2 yr. Lowest values are on the youngest soils with the most harsh environment. The greatest amount of both litter and nitrogen contribution is under the well developed *Pisonia* forest on Kabelle Island. Nitrogen return by litter is up to ten times greater under *Pisonia* than under the poorest *Scaevola.* Some of this nitrogen contribution is from sea birds, as their excrement is ubiquitous on the litter. One litter site on Bikini island under a mixed cover of *Scaevola* and *Dodonaea* averaged about 1200 g/m^2 in weight but we have no nitrogen analysis (Table 28).

Because of the favorable conditions for decomposition, humus accumulation on the soil surface was not a common soil feature. Exceptions are under some *Pisonia* forests, occasional *Tournefortia* stands and *Bruguiera* swamps. In most soils the litter decomposes and residual products are incorporated into the surface horizons. In order to get some concept of rate of litter decomposition we collected leaves from three species and set them out in trays under the species of collection for a 6 month period. Results are given in Table 11. These show up to a 75 percent weight loss over the March to September period which encompasses the end of the normal dry season and the summer wet season. *Cordia* and *Tournefortia* leaves decomposed slower than *Scaevola* but there are not enough samples to attach a statistical significance.

Although humus layers are not a normal component of Rongelap Atoll soils and do not approach those described for Arno Atoll by Stone (1951) they are present in some situations. We sampled these under two species and found amounts ranging from 1000 to over 4000 g/m^2, with up to 175 g/m^2 of nitrogen. Humus under *Tournefortia* was much less in amount, but these plants were on a young soil (Table 12).

Nitrogen and Phosphorus Content of Litter and Soil

The nitrogen and phosphorus contents of litter and soils under a number of species over a range of soil ages is summarized in Table 13. Although the soil classification of "young" or "moderate" age was based on general observations and not substantiated by any measurements, the results show pronounced differences in both nitrogen and phosphorus when the same plant is compared on the two age classes of soils. For example *Tournefortia* litter and surface soil have nitrogen values of 1.72 and 0.70 percent respectively in the "moderate age" soil with 0.67 and 0.22 for similar locations in the "young" soil (Table 13). Species differences are also apparent in both age classes with

Table 11. Weight Loss of Leaf Litter from Three Species of Rongelap Atoll Trees in a Decomposition Study[1]

Species	Initial Dry wt.[2] g	Final Dry wt.[2] g	Loss g	% loss
Scaevola	81.0	19.7	61.3	75.6
Scaevola	89.0	30.8	58.2	65.4
Tournefortia	75.0	36.4	38.6	51.5
Tournefortia	74.8	36.3	38.5	51.4
Cordia	109.0	61.7	47.3	43.4
Cordia	68.2	34.1	34.1	50.0

[1] Decomposition period—3/4/59 to 9/4/59
[2] Weights determined by oven drying subsamples

Table 12. Dry Weight and Nitrogen Content of Humus Under Two Tree Species on Rongelap Atoll

				Total Weight		Nitrogen[1]	
Area	Year	Species	No. Samples	g/m^2	kg/ha	g/m^2	kg/ha
Pit 4	1961	*Pisonia*	1	4,196	41,960	172	1,720
Pit 38	1961	*Pisonia*	8	2,690	26,900	110	1,100
Pit 38	1986	*Pisonia*	1	4,304	43,040	177	1,770
Wash area	1963	*Tournefortia*	3	1,022	10,220	6.1	61

[1] Ave N content *Pisonia* humus—4.11%
Ave N content *Tournefortia* humus—0.60%

Table 13. Average Nitrogen and Phosphorus Content of Litter and Soil under Different Plant Species, Rongelap Atoll[1]

Species	No. Samples for N	Nitrogen (Percent) Soil Depth (cm)				No. Samples for P	Phosphorus (ppm) Soil Depth (cm)			
		Litter	0-2.5	2.5-15.2	15.2-30.5		Litter	0-2.5	2.5-15.2	15.2-30.5
						Moderate Age Soils				
Scaevola	7	1.01	1.12	0.32	0.12	4	500	82	34	8
Tournefortia	8	1.72	0.70	0.25	0.10	1	335	273	35	13
Guettarda	10	1.47	0.95	0.36	0.12	8	179	102	14	10
Pisonia	7	2.57	1.94	0.49	0.22	3	924	206	62	42
Cordia	3	1.27	2.02	0.98	0.50					
Neisosperma (=Ochrosia)	3	1.44	1.04	0.28	0.08	1	1662	1198	35	13
Pandanus	2	1.24	1.11	0.47	0.09	1	66	65	8	8
Pemphis	2	1.44	0.33	0.26	0.11	1	193	146	52	14
Lepturus	2	--	0.45	0.23	0.09	--				
						Young Soils				
Scaevola	3	0.72	0.12	0.07	0.05	1	154	45	29	23
Tournefortia	15	0.67	0.22	0.08	0.03	1	352	141	23	14
Guettarda	7	0.99	0.44	0.21	0.07	1	50	50	36	15
Cordia	1	1.08	0.20	0.06	0.03	1	270	92	35	26

[1] Nitrogen was Kjeldahl; Phosphorus is bicarbonate extractable

Pisonia having the highest values. *Cordia* soils of moderate age are also high in nitrogen. In areas not ordinarily disturbed by humans these species and *Tournefortia* are utilized by sea birds for nesting. As many of the samples came from remote islands the high values of the moderate age samples may reflect a sea bird influence on both nitrogen and phosphorus.

Total Nitrogen in Soils

In order to compare total nitrogen in contrasting soils we utilized bulk density and nitrogen content to estimate total nitrogen in the soil to a depth of 25 cm (Table 14). Some nitrogen exists at greater depths but a 25 cm depth accounts for at least 90 percent of the total in the soil. Pit 6 which represents a young soil on Kabelle Island has only 403 kg/ha of nitrogen, while the *Pisonia* forest area at Pit 38 has almost 13,000. In addition it would have up to 1,500 kg/ha of nitrogen in a humus layer making a total of about 14,500 kg/ha in the soil system. Pit 22 which is in the Rongelap Island coconut plantations is intermediate with 4,500 kg/ha. It does not have a humus layer, but does have some nitrogen in litter form.

Fungi and Algae

Although no systematic survey of soil micro-organisms was undertaken by any of the study groups, some information was collected through cooperative efforts. Selected soil samples collected in September 1959 were sent to Dr. William Bridge Cooke, then at the U.S. Public Health Laboratory at Cincinnati, Ohio. Results of his plate counts of fungi are given in Table 15. Surface soils and well-developed soils have more fungi than at depth in a profile or in open sandy areas. He reported that *Trichoderma viride* was ubiquitous in the samples.

Algal crust layers were sent to Dr. L. W. Durrell (Colorado State University) who identified the following species:

Chroococcum dispersus
" *turgidus*
" *pallidus*
Nostoc commune
" *punetiporme*
Plectonema radiosum

Phormidium subcapitatum
" *retzii*
" *papyraceum*
" *tenue*
Mesotaenium macrococcum
Merismopedia glauca
Nodularia spumigena

Table 14. Total Nitrogen Content (Kg N/ha)of Selected Soil Profiles, Rongelap Atoll

Source	0-2.5 cm	2.5-15.2 cm	15.2-25.5 cm	0-25.5 cm Depth
Pit 6 Kabelle	97	204	102	403
Pit 38 Kabelle	2,280	8,620	2,070	12,900
Pit 22 Rongelap	1,660	1,820	1,120	4,590

Table 15. Estimates of fungi in some Rongelap soils[a].

Soil Location	Description	Colony count per ml sample (estimated average of 5 plates corrected for dilution)
Pit No. 1	Surface Soil	55,800
Pit No. 1	0-2.5 cm	95,200
Pit No. 1	38-40 cm	3,000
Pit No. 1	Side of Soil Pit	50,000
Pit No. 34	0-1.3 cm	67,400
Pit No. 34	43-45 cm	2,000
Sand Spit, Rongelap Is.		1,000
Pit No. 36	0-2.5 cm	5,000
Pit No. 36	25-30 cm	7,000
Pit No. 35	0-2.5 cm	21,600
Pit No. 35	56-58 cm	1,000
Pit No. 35	170 cm	1,200

[a]Counts made by Dr. William Bridge Cooke
Soil samples collected September 1959, and sealed in plastic bags; received by Dr. Cooke 4 Dec. 1959; plated 7 Dec. 1959; counted 14 Dec. 1959.

SOILS AND PLANTS OF ENEWETAK AND BIKINI ATOLLS

Bikini and Enewetak atolls were more impacted by the weapons testing program than Rongelap, as they served as the locations for tests. Therefore the principal objective of soil and plant sampling on these atolls was for radioactivity status. Although the subject is dealt with in some parts of this report (see Tables 18 and 19) the authors were not heavily involved in these studies. Interested readers who want to review this subject are referred to the following publications: Chakravarti and Held, 1961; Donaldson, et al., 1955; Held, 1963; Held, et al., 1965a; Palumbo, 1961; Welander, et al., 1966; Nelson, et al., 1977; Robison, et al., 1987, 1991.

In this section we give results of the chemical analysis of soils in relationship to the condition of the collection areas in 1964, several years after the testing program. We first describe conditions in 1964 by setting up some general disturbance classes. This classification of collection areas should provide readers with a basis for judging impact of the tests as well as vegetation recovery by 1964. No attempt to classify soils of Bikini or Enewetak was made.

1964 Condition

The effect of the nuclear weapon testing on soils and plants is related to the nature of the soil at the time of the test. This is especially true for rate of recovery. Palumbo (1962) considered some of these aspects in discussing recovery of vegetation on Enewetak Atoll. Islets made up mainly of young, sterile soils were more severely damaged and recovered more slowly from the same intensity of test.

Several distinct contrasts were readily apparent in the condition of both soils and vegetation on Bikini and Enewetak in 1964. We therefore used four disturbance classes (Table 16) and attempted to sample across the range of the classes. Descriptions of the classes follow:

Disturbance Class

A. Relatively undisturbed except by construction activities or those effects related to visitation by relatively large numbers of people. Several islands at both Bikini and Enewetak could be cited as examples of this category. The condition of soil and vegetation ranges from mature to immature. Japtan on Enewetak Atoll represents an island of relatively deep mature soils which suffered no major changes during the testing period. Flora and fauna could be said to be somewhat normal and certain areas of undisturbed soils were found, and indeed sampled.

To a limited degree Eneu Island at Bikini could be placed in the same category. Of course, relatively large areas were changed by airfield construction and activities of a large number of personnel. However, some areas had mature coconut trees as of 1964, and seemed to have experienced little soil disturbance. Also, a number of small islets represent soils and vegetation in the younger stages of development, which had suffered

Table 16. Soil disturbance classification by Islets for Bikini and Enewetak Atolls (1964)[a]

Disturbance Class	Island
Bikini	
A	Bokdrolul (Boro)
	Eneu
B	Bikini
C	Nam
D	Aomoen (George)
	Lomilik (Fox)
	Bwikor (Yurochi, Dog)
	Odrik (Uorikku, Easy)
	Eneman (Eninman)
	Bikdren (Bigiren)
	Aerokoj (Airukiiji)
Enewetak	
A	Japtan
	Ikuren (Igurin)
B	Bokombako (Belle)
C	Bokoluo (Bogallua, Alice)
D	Runit
	Enjebi
	Bokinwotme (Edna)

[a]Marshallese names of the islands are listed first, with in some cases familiar previously used or code names given in parentheses.

no major physical destruction. Bokdrolul (Boro) could be cited as an example, as well as Ikuren and Biken (Rigili) on Enewetak.

B. This is the condition under which the vegetation was largely destroyed, probably by fire, but in which the soil was little affected, except at the surface. The best example of this condition is on Bikini Island. The soils, except for areas involved in construction disturbance, appear to be almost intact and little different from the soil of the productive areas of many of the atolls. Organic matter was high to depths of 45 cm, and the nutrient element supply is apparently good. Core samples collected in 1964 are difficult to distinguish from good soils of other atolls. The net effect of this lack of soil disturbance was an explosive re-development of native vegetation. So much growth had developed that it was practically impossible to move across the island.

One could surmise that this soil could be returned to productive coconut culture by reestablishing the destroyed coconut plantations, but recognizing the problem of retained radioactivity. In fact, Eneu and Bikini islands of Bikini Atoll were successfully replanted about 1970.

C. On Bikini Atoll, Nam island soils represent an intermediate state of destruction and redevelopment. Although the authors did not see Nam before the tests, it is obvious that the soils were deep and well developed and must have supported a luxuriant island vegetation. Inspection and collection in 1964 showed that destructive effects were largely confined to surface soils throughout most of the island. Soils still had high organic matter contents to depths of 30 cm, but showed indication of considerable disturbance and destruction at the surface. However, much of the inherent productive capacity of the soil had been retained and natural vegetation was rapidly returning and flourishing. The general rapid improvement was aided by large numbers of terns nesting in the trees. This assessment was confirmed by the 1986 visit to Nam, when almost entire coverage of the island by vegetation was noted.

D. The extreme destruction of soils and vegetation is represented by such islands as Lomilik (Fox) or Aomoen (George) on Bikini, and Runit (Yvonne)and Bokinwotme (Edna) on Enewetak. In these cases, there was almost complete destruction of soils on relatively small islands. Surface soils were probably either vaporized or completely blown away. This was true for both mature and young soils, so that the entire nature of the islet was changed. Recovery of these areas is very much related to redevelopment of soil, and subsequently vegetation. Soil redevelopment is, in turn, related to two different geologic factors. In cases where surface soil was destroyed down to cemented beach rock, redevelopment was materially slowed, and the ability of plants to re-invade much reduced. In cases where loose coral sand was present, or was being washed in by the sea, invasion and soil development proceeded at a more rapid pace. Our studies showed that on Bokinwotme (Edna), soil profile development occurred rather rapidly under *Tournefortia* plants so that after 6 to 10 years of growth, a surface organic horizon was forming. By and large these heavily damaged islands represent a great variety of conditions, none of which will be rapidly cured. However, some spots are

better than others and will continue to improve rapidly as vegetation is re-established and sea birds again inhabit the areas. We have been able to follow a similar sequence of events brought about by natural factors in very young soils on Kabelle Island of Rongelap atoll. Table 16 presents a disturbance classification of all of the islands on both Bikini and Enewetak atolls which we were able to study.

Casual observations which have some bearing on the ability of test areas to again support life are related to the activity of ants and to hermit crabs. Ants of various species seem to be quite abundant in all Marshall Island atolls. We personally observed them in fairly large numbers in even the most severely damaged test areas. They seemed to be normal in all respects.

Hermit crabs were also observed in rather large numbers on the heavily damaged islets. Their major problem seemed to be a shortage of food. As a result, they were observed to be eating bark and leaves of *Tournefortia* trees. In some cases small trees were almost completely girdled.

Chemical Analyses

Chemical analyses of composite soil samples from various islands representing a range of disturbance and from two pits in more detail are given in Table 17. These clearly show the loss of nitrogen and organic matter in severely disturbed soils represented by the crater area samples.

PLANT PHYSIOLOGICAL STUDIES

PLANT NUTRITION

Pot Tests Using Atoll Soils

Pot tests were run in the greenhouse at Seattle and also under a wind and rain shelter at Enewetak. Objectives of these were to ascertain the ability of the soils to supply various mineral nutrients, and the influence of mineral fertilization on the uptake of ^{137}Cs. The depression of ^{137}Cs uptake by fertilization, especially with potassium, had been reported from our earliest trials (Walker, Held and Gessel, 1961), but these experiments confirmed and extended those findings. In the greenhouse in Seattle, maize was grown in a surface soil collected near the well on Rongelap Island. A summary of the principal results is given in Table 18.

Although as in the earlier trials, potassium fertilization depressed ^{137}Cs uptake, an experiment under atoll climate conditions was conducted at Enewetak for additional verification. Surface soil (ca. 20 cm depth) was collected in a coconut grove near the center of the relatively undisturbed small island of Japtan. A total elemental analysis of this soil is included in Table 17. The dark colored soil was sieved through a 1/2 inch mesh at the collection site. At the Enewetak Marine Biological Laboratory, following

Table 17. Elemental Analysis of Contrasting Bikini and Enewetak Soils.[1]

			Percent				ppm					
Island		Dist. Class	N %	P %	Ca %	Mg %	Na	K	Fe	Mn	Cu	Zn
Composite Soils, Surface 15 cm												
	Vegetation											
Ikuren	*Pisonia*	A	0.31	0.34	36.8	0.73	940	70	37.9	1.80	29.4	12.0
Japtan	*Pisonia*	A	0.84	4.38	31.9	0.96	1,040	260	92.2	8.40	10.3	18.1
Runit	Open crater	D	0.01	0.07	36.9	1.21	1,120	70	607.	5.60	26.9	8.8
Eneu	Coconut grove	A	0.42	0.33	36.2	0.80	1,030	90	138.	2.00	29.3	10.4
Bikini	*Pandanus*	B	0.60	0.95	31.7	2.29	1,010	100	73.5	2.90	44.9	12.7
Lomilik	Crater area	D	0.06	0.11	35.6	1.99	980	50	23.9	1.30	19.8	8.7
Nam	*Tournefortia*	C	0.10	0.04	35.2	2.08	1,090	80	35.0	0.80	21.7	20.0
Eneman	Crater area	D	0.02	0.07	38.0	4.38	1,010	60	21.3	0.70	21.6	10.9
Profile Survey												
Soil Pit 11	**Depth cm**											
Bikini	0.0 - 1.25	B	1.15	1.38	27.7	1.73	760	170	139.	4.80	29.5	24.6
Bikini	1.25 - 2.5		0.89	1.27	30.1	2.06	900	110	118.	3.50	35.2	19.9
Bikini	2.5 - 5.0		0.75	1.34	31.3	1.87	890	130	120.	2.00	33.4	19.5
Bikini	5.0 - 7.5		0.35	1.23	34.1	1.97	1,000	100	94.6	1.50	35.7	18.0
Bikini	7.5 - 10.0		0.31	0.72	33.8	1.55	910	80	50.9	0.70	38.0	17.9
Bikini	10.0 - 12.5		0.31	0.65	34.5	1.47	913	71	44.4	0.80	30.4	14.6
Bikini	12.5 - 15.0		0.20	0.91	34.4	0.99	1,060	78	75.9	.080	26.6	13.1
Bikini	15.0 - 17.5		0.15	0.93	33.6	1.28	776	77	50.5	0.60	24.2	12.8
Bikini	17.5 - 20.0		0.20	0.59	33.7	1.73	865	79	40.2	0.60	23.0	14.0
Bikini	20.0 - 22.5		0.12	0.56	34.3	1.25	764	70	37.7	0.80	20.0	15.0

Table 17. (continued)

			Percent				PPM					
Island	Depth cm	Dist. Class	N %	P %	Ca %	Mg %	Na	K	Fe	Mn	Cu	Zn
Bikini	25.5 - 25.0	B	0.12	0.35	35.7	1.22	773	62	26.4	0.60	20.2	12.4
Bikini	25.0 - 30.0		0.08	0.30	32.6	1.53	882	64	23.8	0.50	14.0	14.1
Bikini	30.0 - 37.5		0.10	0.31	34.9	1.29	863	62	26.3	0.60	14.5	13.3
Bikini	37.5 - 50.0		0.07	0.14	34.5	1.90	931	61	15.0	0.30	10.0	13.3
Bikini	50.0 - 65.0		0.03	0.04	34.3	2.78	970	63	11.3	0.50	7.0	12.1
Aomoen	0.0 - 1.25	D	0.04	0.04	34.5	2.18	790	62	48.3	0.50	6.8	12.8
Aomoen	1.25 - 2.5		0.03	0.05	34.1	2.19	871	61	134.0	0.90	11.4	13.0
Aomoen	2.5 - 5.0		0.03	0.04	35.5	2.06	1,000	61	220.4	0.30	8.0	13.8
Aomoen	5.0 - 7.5		0.03	0.04	35.5	2.29	962	56	109.0	0.70	7.2	13.0
Aomoen	7.5 - 10.0											
Aomoen	10.0 - 12.5		0.04	0.04	35.6	1.89	901	56	205.0	0.60	7.0	13.0
Aomoen	12.5 - 15.0		0.03	0.02	35.0	1.81	821	54	11.3	0.10	6.9	13.2
Aomoen	15.0 - 17.5		0.02	0.02	33.8	2.38	841	53	10.0	0.10	5.3	13.5
Aomoen	17.5 - 20.0		0.03	0.02	35.4	1.69	840	52	7.5	-	3.9	11.8
Aomoen	20.0 - 22.5		0.01	0.03	35.4	1.98	740	50	6.3	-	4.1	10.7

[1] Nitrogen by Kjeldahl; other elements from acid digest (see page 11)

Table 18. Maize Grown in the Greenhouse on Rongelap Well Soil (Expt. 59-471)

Fertilization*	Ave. Dry yield (g)	Ave. K in Shoots (%)	Ave ^{137}Cs in Shoots (becq/g)
$N_{4.48}$ $P_{4.48}$ K_0	2.00 ± 0.30	1.96	0.150 ± 0.027
$N_{4.48}$ $P_{4.48}$ $K_{2.24}$	2.93 ± 0.50	2.46	0.105 ± 0.010
$N_{4.48}$ $P_{4.48}$ $K_{4.48}$	3.02 ± 0.14	3.42	0.083 ± 0.011

* Subscripts refer to hundreds of kilograms per hectare equivalent of N, P_2O_5, or K_2O respectively

Table 19. Methods Used for Plant Tissue Analyses.

Ca	Mostly EDTA titration; some by titration of oxalate precipitate with permanganate[a]
Mg	Mostly by EDTA titration; some by colorimetric estimation of $MgNH_4PO_4$ precipitate[a]
K, Na	By flame photometry with Beckman DU flame attachment[a]
N	By Kjeldahl digestion, distillation, and titration[a]
P	By the molybdivanadate colorimetric method[a]
Fe	By orthophenanthroline colorimetric method[b]
Mn	By the permanganate colorimetric method[a]
Zn	By the Zincon colorimetric method[b]
Cu	By ion exchange followed by the Zincon method[b]
B	By the curcumin colorimetric method[c]

[a] Methods adapted from Jackson (1958)
[b] Methods adapted from Sandell (1959)
[c] Procedure of Dible et al. (1954)

methods similar to those of Jenny et al. (1950), 6-quart portions of the soil were mixed on a plastic sheet with the appropriate fertilizer solution, placed in 7-quart wastebasket-type containers with drain holes, moistened with distilled water, then each planted with five seeds of a hybrid maize. The containers were placed in a random arrangement in a rain and wind shelter near the laboratory (Figure 12). The fertilizer materials were NH_4NO_3, H_3PO_4, and KC1, with iron added at 75 mg Fe per container using the EDTA complex. After about 30 days the shoots were harvested, divided into stem and upper and lower leaf fractions, oven dried at Enewetak, then ground to 40 mesh using a Wiley mill in Seattle, and analyzed by methods listed in Table 19. Radioactivity of principal isotopes was also assayed: ^{137}Cs by gamma ray spectroscopy using a 3-inch Th activated NaI crystal and ^{90}Sr by standard procedures.

The yields and analytical results for the various treatments are given in Table 20. There were strong responses in yield to additions of nitrogen and of potassium, but phosphorus added at the P_4 level had little influence. Phosphorus at the P_8 level depressed growth markedly, probably because it reduced the availability of iron or other micronutrients. The depression of calcium and magnesium by potassium addition is very obvious in the upper leaves as expected, and this is evident also for magnesium in the lower leaves and for both calcium and magnesium in the stems. The low supplying capacity of this soil for potassium is shown both by the low levels in the tissue when potassium was not added and by the mobility of potassium, with upper leaves being higher than lower leaves even in treatments which received potassium. The marked depression of ^{137}Cs uptake by potassium fertilization is consistent throughout the experiment, and depressions are great enough that even at the highest yields dilution could not explain the reductions. The ^{90}Sr activities were appreciably higher in the lower than in the upper leaves, a pattern which closely followed that of calcium. From the standpoint of general fertility, there was marked response to both nitrogen and phosphorus additions despite the high total amounts in the Japtan soil (Table 17). Magnesium contents of the tissue are high, approaching calcium on a percentage basis thus often exceeding calcium on a chemical equivalent basis. This is consistent with the substantial levels of exchangeable magnesium in Rongelap soils (Tables 2-6), which is likely the case for Bikini soils as well.

Plant Tissue Analyses

Many samples of plant tissues were collected on each of the eight expeditions during the period 1958 to 1964. The results of analyses of some food items were reported (Chakravarti & Held, 1961); most of the rest of the samples were of foliage, although some collections of wood and bark were made. Analyses were made for major cations, nitrogen, phosphorus, and micronutrients on a sizable number of these samples, mostly of coconut palm, *Tournefortia*, *Scaevola*, and *Guettarda*. The methods of analysis are given in Table 19. In most cases the elements were brought into solution by dry ashing at 450-500°C, then dissolving the ash in dilute HC1.

The analytical results are presented in Tables 21 through 24. A general evaluation of these follows, with respect to each element:

Figure 12 Maize in pot cultures in experimental shelter at Enewetak

Table 20. Yield, Chemical Compositon, and ^{90}Sr and ^{137}Cs Activities in Maize Grown in Pot Cultures at Enewetak Atoll

Treatment[a]		Mean Dry Weights (g)		Mean Chemical Composition (% Dry wt.)					Mean ^{137}Cs (Entire Shoot)	Mean ^{90}Sr
		Plant Parts	Total Shoot	Ca	Mg	K	N	P	becq/g	becq/g
	Upper lvs	1.25		1.15	0.91	0.42	1.44	0.11		6.68
Control	Lower lvs	0.27	2.12 ± 0.17	3.05	1.83	0.076	1.24	0.17	4.50	12.7
	Stems	0.59	(26%)[b]	0.81	0.75	0.47	1.03	0.23		5.50
	Upper lvs	0.93		0.95	0.81	0.55	—	0.15		4.55
Fe only	Lower Lvs	0.26	1.56 ± 0.34	2.16	1.20	0.093	—	0.28	3.83	8.67
	Stems	0.36	(19%)	0.88	0.79	0.79	—	0.30		4.97
	Upper lvs	5.52		0.64	0.34	2.81	1.86	0.25		2.23
$N_{2.24}P_{4.48}K_{2.24}Fe$	Lower lvs	0.43	8.20 ± 3.98	2.28	0.57	1.75	1.19	0.16	0.80	7.40
	Stems	2.45	(100%)	0.85	0.62	4.48	1.53	0.29		4.33
	Upper lvs	1.51		0.56	0.28	2.89	—	0.17		2.12
$N_0P_{4.48}K_{2.24}Fe$	Lower lvs	0.32	2.37 ± 0.54	1.86	0.60	2.41	—	0.12	0.60	6.65
	Stems	0.59	(29%)	0.66	0.40	6.07	—	0.44		2.57
	Upper lvs	4.42		0.63	0.34	2.60	—	0.16		2.28
$N_{2.24}P_0K_{2.24}Fe$	Lower lvs	0.46	7.28 ± 1.62	3.11	0.55	2.14	—	0.064	0.717	7.08
	Stems	2.40	(89%)	0.63	0.51	4.73	—	0.24		2.30
	Upper lvs	1.33		1.43	1.08	0.39	1.62	0.32		4.75
$N_{2.24}P_{4.48}K_0Fe$	Lower lvs	0.50	2.23 ± 0.72	2.60	1.21	0.13	1.72	0.49	4.83	7.37
	Stems	0.40	(27%)	1.29	1.16	0.67	1.46	0.72		5.75
	Upper lvs	5.05		0.56	0.26	3.33	—	0.24		4.52
$N_{2.24}P_{4.48}K_{4.48}Fe$	Lower lvs	0.41	8.19 ± 4.60	2.47	0.55	3.16	—	0.22	—	4.02
	Stems	2.28	(100%)	0.62	0.35	6.17	—	0.32		2.88
	Upper lvs	2.50		0.89	0.41	4.18		0.31		3.17
$N_{2.24}P_{8.96}K_{2.24}Fe$	Lower lvs	0.55	4.22 ± 1.69	2.83	0.66	3.74		0.30	—	6.20
	Stems	1.18	(51%)	0.82	0.49	6.02		0.38		2.57

[a]Subscripts of fertilizer treatments refer to hundreds of kilograms per hectare of N, P_2O_5, or K_2O respectively.
[b]Percentages compare yields with $N_{2.24}P_{4.48}K_{2.24}Fe$ treatment.

Calcium - The contents in the dicotyledenous species were high, and in most cases higher in lower than in upper leaves, as would be expected for an immobile element. In palm the contents were lower, characteristic of a monocot, and in the few comparisons available lower leaves again had higher contents than upper leaves. This species collected on Bikini/Enewetak showed generally lower values than collections from Rongelap. The possibility of a systematic analytical error accounting for these lower values for Bikini samples cannot be ruled out, although even the lowest contents are substantial for this element.

Magnesium - The contents of this element are appreciable, and in almost all cases are higher in lower than in upper foliage, which in a mobile element indicates a more than adequate supply to the plant. In palm, magnesium sometimes equalled or even slightly exceeded calcium in percentage and more often on a chemical equivalent basis, which was surprising in view of the dominance of calcium in the substrate. However, this can reflect the appreciable exchangeable magnesium in the soils (Tables 2-6) and very likely also the high magnesium levels in ground waters (Table 27). The samples from Bikini/Enewetak (*Tournefortia*) were appreciably lower in magnesium than the Rongelap material, and the contents of lower leaves were usually not equal to those of the upper leaves.

Potassium - For all species the upper leaves seem to have fairly good levels of potassium, but the lower leaves are almost always lower and sometimes very low in this element, indicating from this mobility a limiting supply of potassium. Again, *Tournefortia* from Bikini/Enewetak was lower in potassium status than material from Rongelap.

Sodium - As might be expected near the sea, sodium contents were substantial in the dicotyledonous species, but this did not prove to be the case for the monocotyledon, coconut palm. In the dicots, the lower leaves commonly had higher levels than the upper leaves, and it was common for sodium to be higher than potassium. The collected foliage was not washed, so aerosol sodium chloride deposited on the leaves may have increased sodium values. However, *Scaevola*, *Tournefortia* and other species showed strong uptake of sodium in greenhouse experiments (Léskó, 1968; Walker and Gessel, 1991), and palm (Table 24) shows low sodium in the field collections.

Nitrogen - Contents of this element are often low, especially on the beach fringes of the islands. Also this is very evident in recently planted coconut trees. In the centers of islands, where soil organic matter is higher and where bird roost is common, nitrogen levels can be much higher. Thus, nitrogen values vary appreciably among the collections, but in most cases nitrogen in the lower leaves is less than in the upper leaves, indicating a short supply of this mobile element. The plant condition rating of "good" in *Tournefortia* on Bikini and Enewetak (Table 22) is mostly associated with higher nitrogen levels.

Table 21. Analyses of foliage of *Tournefortia* (*Messerschmidia*) plants from Rongelap Atoll

						Macroelements (% of dry tissue)						Micronutrients (mg/kg dry tissue=ppm)			
Sample	Date of Coll	Atoll	Island	Location on Island	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	B	137Cs becq/dry g
Mess-106A,B	858	Rongelap	Rongelap	Over Pit 25	UL[a]	2.14	0.62	1.30	2.74	1.84	0.23				4.00±0.13
				at weather sta.	LL	3.48	0.86	0.26	4.73	0.88	0.21				2.50±0.12
Mess-200	959	Rongelap	Rongelap	(w. tip of island)	UL	2.40	0.65	1.97	1.99	-	0.32				
					LL	4.40	0.81	0.69	2.50	-	0.51				
Mess-6A,B	858	Rongelap	Kabelle	Near Pit 6	UL	3.96	0.52	2.13	1.99	2.50	0.23				7.17±0.084
					LL	6.78	0.64	0.60	3.45	1.13	0.17				4.75±0.22
Mess-128A,B	359	Rongelap	Kabelle		UL	3.61	0.43	1.80	2.23	-	0.26				5.83±0.10
					LL	7.07	0.62	1.04	2.23	-	0.21				8.67±0.17
Mess-129A,B	359	Rongelap	Kabelle		UL	2.95	0.46	1.95	1.65	-	0.29				8.33±0.12
					LL	3.15	0.55	1.22	2.92	-	0.16				11.2±0.13
Mess-130A,B	359	Rongelap	Kabelle		UL	3.38	0.47	1.44	2.43	-	0.16				3.67±0.083
					LL	8.74	1.01	0.13	2.13	-	0.075				1.83±0.067
Mess-209A,B	959	Rongelap	Kabelle	Wash Area	UL	3.85	0.70	1.00	1.96	2.04	0.22				
					LL	5.18	0.99	0.60	2.19	1.34	0.30				
Mess-210A,B	959	Rongelap	Kabelle	Wash Area	UL	4.43	0.94	0.83	1.66	1.45	0.24				
				12m E of 209	LL	5.07	0.92	0.27	2.20	0.91	0.28				
Mess-211A,B	959	Rongelap	Kabelle	E. end *Pisonia*	UL	2.79	0.54	2.70	1.59	2.78	0.31				
				fert. plots	LL	3.49	0.64	2.04	2.16	2.25	0.30				
Mess-120	363	Rongelap	Kabelle	Plot X	UL	3.28	0.63	1.24	5.60	-	0.21	48	23		
Mess-121				near cistern	LL	5.25	0.77	0.35	4.30	-	0.16	43	16	84	
Mess-128	363	Rongelap	Kabelle	Beach area	UL	3.70	0.85	1.53	1.95	-	0.24	28	25		
Mess-129				near cistern	LL	4.72	0.43	1.10	0.63	-	0.18	30	17		
Mess-207	959	Rongelap	Rochi	Along lagoon	UL	2.16	0.46	1.82	2.05	2.13	0.23				
				beach	LL	3.41	0.70	1.14	3.16	1.65	0.24				
Mess-214	959	Rongelap	Lomuilal	60m fr. lag.; 150m	UL	2.94	0.50	1.74	1.91	2.10	0.19				
				fr. SE tip of island	LL	4.63	0.57	0.75	2.72	1.90	0.18				
Mess-215	959	Rongelap	Naen	DUKW landing	UL	3.50	0.55	1.64	2.11	2.52	0.19				
					LL	4.63	0.57	0.90	3.12	1.90	0.15				
Mess-226	959	Rongelap	Naen	SE corner of island	UL	3.65	0.61	1.76	1.85	2.12	0.14				
				SW corner of island	LL	5.25	0.70	1.08	2.63	2.02	0.075				
Mess-228		Rongelap	Gogan	Open beach	UL	3.85	0.58	1.67	2.35	2.52	0.17				
				area-W. end	LL	5.04	0.68	0.65	3.24	1.33	0.098				

[a] UL = upper leaves; LL = lower leaves

Table 22. Analyses of foliage of *Tournefortia (Messerschmidia)* plants on Bikini and Enewetak Atolls collected in August 1964

						Macroelements (% of dry tissue)					Micronutrients (mg/kg dry tissue=ppm)				
Date of Coll	Atoll	Island	Location on Island	Plant Condition	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	Cu	Zn
864	Bikini	Aerokoj	Old airport area	Poor	UL[a]	2.46	0.95	0.99	1.48	1.40	0.27	26	21	10	26
			variable vigor;	Mottled	UL	1.19	0.40	0.83	2.60	2.40	1.40	27	11	13	21
			ferns present	Good	Bud	8.28	3.28	1.18	1.50	2.09	1.85	20	5.5	4,5	23
				Good	LL	0.94	0.37	0.81	2.78	0.90	0.41	9.5	18	16	104
				Mottled	LL	1.03	0.46	0.33	2.43	0.97	0.23	13	9.4	14	53
864	Bikini	Bikini	Near present	Poor	UL	1.47	0.33	1.14	1.75	0.93	0.80	19	8.5	6.5	13
			truck landing	Poor	LL	1.22	0.34	0.61	1.70	0.90	0.16	16	7.4	3.8	17
			along lagoon	Good	UL	1.50	0.41	1.80	1.65	1.97	1.00	19	3.0	9.3	11
			shore NW from village area.	Poor	LL	2.30	0.34	0.29	2.50	0.50	0.40	12	11	1.5	68
			Vigor poor	Poor	LL	2.14	0.90	1.18	2.55	1,02	0.15	16	21	1.8	26
			on beach but	Good	LL	1.41	0.52	1.89	2.28	1.26	0.095	14	19	17	19
			good in interior	Good	LL	1.03	0.25	0.70	2.68	1.24	0.092	18	23	6.5	11
				Poor	LL	1.63	0.21	0.66	2.60	0.62	0.077	5.8	14	2.5	30
864	Bikini	Eneman	Disturbed site near crater		L	3.69	0.76	1.36	0.80	1.47	0.24	17	9	29	57
864	Bikini	Eneu	Interior near old	Poor	LL	3.30	1.05	1.23	3.35	1.09	1.75	28	11	20	70
			recreational bldg.	Good	LL	2.73	0.53	0.35	3.95	1.14	0.65	43	8.5	34	21
			Varying dis-	Poor	UL	0.67	0.16	1.63	1.98	1.77	0.27	16	13	11	48
			turbance	Good	UL	0.81	0.23	1.43	1.78	2.77	0.12	25	19	6.8	21
864	Bikini	Nam	Disturbed	Poor	UL	2.12	0.50	1.51	1.55	1.23	0.13	15	12	5.8	16
				Poor	LL	2.06	0.38	0.78	2.78	0.69	0.10	12	17	14.5	19
864	Bikini	Lomilik	Very disturbed area;	Good	UL	0.98	0.41	1.23	1.98	2.11	0.18	145	19	4.8	18
			soil good and poor	Poor	LL	0.98	0.49	0.70	2.65	0.66	0.089	6.4	14	6.8	35
			mess present		LL	1.09	0.47	0.96	2.43	0.75	0.12	10	16	13	28
					L	2.84	0.67	1.85	0.70	1.27	0.30	16	3.5	12	25
864	Enewetak	Ikuren	Near Helipad	Poor	UL	2.01	0.62	0.35	1.88	1.05	1.00	1.5	9.0	5.5	15
864	Enewetak	Japtan	Disturbed on sur-	Good	UL	5.00	0.34	0.40	2.35	2.44	1.05	36	7.5	16	50
			face; good soil	Poor	LL	2.63	0.56	0.18	2.00	0.53	0.30	110	15	2.8	41
				Good	L	0.90	0.32	0.34	2.40	1.57	0.090	27	18	7.8	56
					L	2.06	0.36	0.88	1.83	1.85	0.26	36	20	12	52
864	Enewetak	Runit	Young, disturbed soil.		L	2.24	0.96	1.08	0.90	1.14	0.31	40	32	48	100
864	Enewetak	Bokinwotme	Center was highly disturbed		L	2.91	0.71	2.08	0.60	2.20	0.28	25	13	38	22

[a] UL = upper leaves; LL = lower leaves; L = general leaf sample

Table 23. Analyses of foliage of *Scaevola* (Sca), *Guettarda* (Gue) and Squash (Squ) Plants collected on Rongelap Atoll

						Macroelements (% of dry tissue)						Micronutrients (mg/kg dry tissue=ppm)			
Sample	Date of Coll	Atoll	Island	Location on Island	Type of Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	B	^{137}Cs becq/dry g
Sca-120A	858	Rongelap	Rongelap	W. of Pit 23	UL[a]	1.78	0.42	2.97	0.95		0.16				0.98±0.083
Sca-120B					LL	2.79	0.60	0.89	1.73		0.23				2.33±0.13
Sca-103A	858	Rongelap	Rongelap	9m NE of Pit 24	UL	1.44	0.42	3.84	0.83		0.17				0.85±0.050
Sca-103B					LL	2.53	0.57	1.49	1.40		0.15				2.17±0.13
Sca-104A	858	Rongelap	Rongelap	9m NE of Pit 21	UL	1.79	0.52	3.28	0.68		0.16				1.27±0.085
Sca-104B					LL	2.52	0.82	1.15	1.76		0.21				3.33±0.13
Sca-105A	858	Rongelap	Rongelap	2-3m NE of Pit 25	UL	1.41	0.64	1.33	1.35		0.20				1.83±0.10
Sca-105B					LL	2.27	1.24	0.48	1.34		0.26				2.50±0.12
Sca-6A	858	Rongelap	Kabelle	Near Pit 6	UL	2.05	0.49	1.96	1.68	1.72	0.27				4.00±0.10
Sca-6B					LL	3.25	0.89	0.33	1.99	0.93	0.31				3.83±0.10
Sca-131A	359	Rongelap	Kabelle		UL	1.79	0.54	1.64	1.25		0.24				3.00±0.27
Sca-131B					LL	3.05	0.84	0.32	1.51		0.36				3.33±0.10
Sca-132A	359	Rongelap	Kabelle		UL	2.91	0.56	1.63	1.00		0.31				4.00±0.10
Sca-132B					LL	3.18	0.82	0.70	1.21		0.46				5.50±0.12
Sca-133A	359	Rongelap	Kabelle		UL	1.86	0.54	1.19	1.25		0.25				3.67±0.083
Sca-133B					LL	2.94	0.77	0.32	1.20		0.27				3.67±0.083
Sca-182	961	Rongelap	Anielap	w/ old btrys.	L	3.11	1.30	1.22	1.97	1.59	0.33	109	20	68	
Sca-183	961	Rongelap	Anielap	w/o old btrys.	L	2.19	0.68	2.28	1.12	1.41	0.39	200	15	51	
Sca-118	363	Rongelap	Kabelle	Plot X near Cistern	UL	2.69	0.62	1.90	1.37	2.01	0.29	48	37		
Sca-119					LL	2.99	0.75	1.25	1.89	1.45	0.32	33	28		
Sca-126	363	Rongelap	Kabelle	Beach area near cistern	UL	1.89	0.57	1.92	1.74	1.21	0.21	29	27		
Sca-127					LL	2.82	0.76	1.09	1.94	0.46	0.24	35			
Gue-180	961	Rongelap	Anielap	w/ old btrys.	UL	0.92	0.41	0.92	0.92	0.97	0.14	21	3.8	50	
					LL	1.32	0.29	0.59	0.68	0.39	0.15	11	4.0		
Gue-181	961	Rongelap	Anielap	w/o old btrys.	UL	1.59	0.52	1.70	0.73	0.90	0.67	22	3.8	64	
					LL	2.05	0.57	1.05	0.60	0.51	0.13	18	4.8		
Gue-122	363	Rongelap	Kabelle	Plot X	UL	1.44	0.30	2.23	0.30	1.69	0.20	30	5.8	48	
Gue-123					LL	2.01	0.47	1.92	0.51	0.81	0.33	24	2.3		
Gue-130	363	Rongelap	Kabelle	Near cistern	UL	1.37	0.34	1.21	0.53	1.47	0.19	23	21		
Gue-131					LL	2.21	0.43	1.04	0.72	0.59	0.18	21	33		
						8.06	1.76	1.83	0.10	2.62	0.27				
Squ-110A	858	Rongelap	Eniaetok	House at ship landing	UL	16.8	3.16	0.94	0.11	1.15	0.23				
Squ-110B					LL										

a UL = upper leaves; LL = lower leaves; L = mixed upper and lower leaves

Table 24. Analyses of coconut palm foliage collected on Rongelap Atoll

	Location on Island	Date of[a] Coll	Fertilizer[b] Treatment	Type of[c] Tissue	Macroelements (% of dry tissue) Ca	Mg	K	Na	N	P	Micronutrients (mg/kg dry tissue=ppm) Fe	Mn	Cu	Zn	B	^{137}Cs becq/dry g
					Rongelap Island											
Row 1	Rows just south		Ca nitrate		0.54	0.35	1.58	0.14	0.54	0.11	39				28	0.47
2	of village[d]		"		0.69	0.33	1.22	0.28	0.50	0.098	32					
3			Uramite		0.57	0.41	1.65	0.23	0.50	0.14	26				20	0.33
4			"		0.54	0.42	1.40	0.29	0.85	0.11	22				34	0.57
5		864	$(NH_4)_2SO_4$	c	0.57	0.51	1.31	0.14	0.51	0.11	42				26	0.43
6			"		0.61	0.52	1.30	0.29	0.75	0.31	30					
7			NH_4NO_3		0.71	0.21	1.42	0.28	0.68	0.11	34					
8			"		0.53	0.27	1.75	0.15	0.63	0.14	27					
9			"		0.54	0.17	1.50	0.22	0.57	0.16	25					
Row A	Additional rows		KCl		0.51	0.28		0.058	0.59	0.14	18				18	0.30
B	south of village [d]		K_2SO_4		0.50	0.37		0.080	0.71	0.61	24				10	0.17
C			NH_4NO_3 + Fe spray		0.51	0.26		0.16	0.74	0.15	28				25	0.42
D		864	NH_4NO_3; KCl; Fe chel.	c	0.55	0.28		0.16	0.60	0.14	24				20	0.33
E			$MgNH_4PO_4$		0.47	0.22		0.28	0.64	0.18	15				29	0.48
1			No fertilizer		0.54	0.42		0.18	0.59	0.14	25				20	0.33
2			"		0.54	0.38		0.23	0.58	0.14	24				41	0.68
Row I	Rows in		Multitracin		0.65	0.62	0.21	0.31	0.97	0.11	65	17	9.4	16		
II	swale area[e]		No fertilizer		0.57	0.33	0.36	0.51	1.02	0.14	38	8.4	9.0	14		
III			Fe-Tracin		0.73	0.42	0.49	0.44	0.91	0.11	15	3.2	7.6	13		
IV		864	Control	c	0.61	0.36	0.66	0.69	0.90	0.10	14	1.6	8.8	13		
V			Fe-Tracin + Mn, Zn, $CuNH_4PO_4$		0.47	0.43	0.24	0.66	1.01	0.098	50	12	8.0	15		
VI			Fe, Mn, Zn, $CuNH_4PO_4$		0.46	0.38	0.20	0.46	0.98	0.11	25	24	8.4	16		
VII					0.50	0.43	0.25	0.49	1.10		37	19	6.6	14		
Row I	Rows near		No treatment		0.89	0.41	0.37	0.13	1.27	0.17	24	9.4	12	30		
I	soil pit no. 1[e]		"		0.72	0.74	1.00	0.32	1.27	0.18	20	13	12	15		
II			Unchelated Tracin		0.75	0.76	0.34	0.45	1.12	0.10	43	23	8.0	30		
II			Multi-Tracin	c	0.61	0.42	0.36	0.35	0.84	0.099	70	13	7.2	13		
III		864	No Treatment		0.91	0.49	0.35	0.43	0.95	0.12	12	9.4	8.2	13		
III			"		0.75	0.79	0.30	0.43	1.42	0.28	50	12	10	15		
IV			Fe-Tracin		0.82	0.71	0.31	0.39	1.18	0.17	21	5.6	9.4	15		
IV			"		0.81	0.44	0.55	0.37	0.94	0.18	27	5.2	14	6.6		
V			Fe-Tracin+Mn, Zn, Cu,NH_4PO_4		0.67	0.54	0.54	0.50	0.99	0.095	32	12	11	29		
V			"		0.55	0.40	0.60	0.41	0.69	0.11	18	24	16	25		
VI			Fe, Zn, NH_4PO_4		0.96	0.55	0.20	0.51	0.88	0.093	18	3.4	14	23		
VI			"		0.67	0.35	0.84	0.50	1.09	1.12	40	7.4	14	22		
VII			Fritted Trace Elements		0.61	0.32	0.55	0.55	0.88	0.12	43	23	14	14		
VII			"		0.82	0.75	0.29	0.35	1.12	0.12	18	12	12	18		

Table 24, continued

Location on Island	Date of Coll	Fertilizer Treatment	Type of [c] Tissue	Macroelements (% of dry tissue) Ca	Mg	K	Na	N	P	Micronutrients (mg/kg dry tissue=ppm) Fe	Mn	Cu	Zn
				Kabelle Island									
Near Cistern	961	Fe, Mn, Zn	L		0.31	1.14	0.62	0.82	0.088	32	2.4		
Near Cistern	961	Untreated	L		0.52	1.24	0.65	0.78	0.11	22	33		
Lagoon Beach	363	Fe Chel. spray	UL (green)	0.32	0.50	1.49	0.75	1.47	0.18	35	9.8		
		Tree 39 9/61	LL (green)	1.09	0.73	0.49	0.70	1.25	0.16	18	4.8		
Lagoon Beach	363	Fe, Mn, Zn	UL (yellow)	0.20	0.28	1.69	0.57	0.85	0.11	10.5	19		
		Tree 21 3/61	LL (yellow)	0.44	0.37	0.50	0.47	0.73	0.073	8.1	9.1		
Lagoon Beach	363	Fe Chel. 9/61	L (yellow)	0.47	0.42	1.28	0.72	0.92	0.17	10.7	55		
Lagoon Beach	363	Fe Chel 9/61	UL (green)	0.37	0.48	1.90		1.24	0.16	26	24		
		Tree 34	LL (green)	0.88	0.60	0.28		1.17	0.12	17	8.9		
Lagoon Beach	363	Fe Chel. 9/61	L (very yellow)	1.50	0.90	1.58	1.11	1.46	0.16	17	3.2		
Plot x	363	No Treatment	UL	0.15	0.10	1.80	0.32	0.91	0.17	31	11		
Plot y	363	No Treatment	UL		0.18	1.92	0.39	0.83	0.19	29	3.8		
			LL	0.76	0.60	0.50	0.29	1.13	0.17	21	3.5		
Lagoon Beach	864	No Treatment	L (poor)	0.84	0.59	0.40	0.33	0.73	0.099	33	11	14	7.3
Lagoon Beach	864	No Treatment	L (poor)	0.85	0.61	0.76	0.71	0.85	0.085	17	2.2	15	6.5
Soil Pit 7	864	No Treatment	L (good)						0.15	25	4.0	15	9.3
Lagoon Beach	864	No Treatment	L	1.50	1.20	0.58	0.15				2.4	10	11
Lagoon Beach	864	400 ml F.T.E. 8/63	L (good)	0.48	0.29	0.54	0.30	1.03	0.13	28	56	14	17
Lagoon Beach	864	200 ml FeEDTA 3/61	L (good)	0.64	0.44	0.50	0.46	0.84	0.16	22	6.4	14	17
Lagoon Beach	864	400 ml F.T.E. 3/61	L	1.02	0.27	0.58	0.29	1.05	0.17	28	78	17	75
Lagoon Beach	864	$FeNH_4PO_4$ 9/61	L (fair)			0.33	0.50	0.90	0.11	25	11	14	12
Lagoon Beach		Fe EDTA spray 9/61 + $FeNH_4PO_4$	L (good)	0.85	0.51	0.38	0.36	0.83	0.099	22	1.8	14	75
Lagoon Beach		200 ml Multitracin 8/63	L (good)	0.45	0.58	0.67	0.54	1.27			51	11	18

[a] Date of collection gives month followed by year (e.g. 864=Aug., 1964)
[b] Typically 450g of fertilizer salts were worked in around each of the some 15 young plants in the row trials. Micronutrient materials were similarly worked in, about 200 ml of dry material per seedling tree, or sprayed to dripping. "Tracin" is a Crown-Zellerbach patented name for lignin-based micronutrient complexing materials. F.T.E. = the sparingly soluble Fritted Trace Elements (Ferro-Enamel Corp.)
[c] Most samples were from seedlings 1-2 m tall. Center pinnae were cut from 1 or 2 leaves of each of several plants in the Rows, or from single plants at Kabelle Island.
[d] These rows were fertilized 9/59 at establishment, and retreated 9/61 and 8/63.
[e] These trials near Pit 1 and in the swale area were established and fertilized 3/63.

Phosphorus - These values vary widely, probably reflecting the amount of soil organic matter as well as the spotty nature of bird roosting and droppings. The young coconut trees in the plantations were mostly rather low to very low in phosphorus. Among the dicot trees, sometimes concentrations in the lower leaves were less than in the upper leaves, indicating inadequate phosphorus supply; but in other cases the values for lower leaves were higher, indicating adequate or even excess supply.

Iron and Manganese - As to be expected in calcium carbonate dominated soils with pHs of 7 to 8, these elements proved to be low to very low. This is correlated with widespread chlorosis in young coconut trees, but chlorosis seems to be absent in older coconuts and in the native trees. Possibly this can be attributed to more extensive rooting.

Copper - Some copper values are low, especially in *Tournefortia from* Bikini (Table 22), but most copper levels seem to be in an adequate range.

Zinc - A few zinc values are low (10 ppm) in the coconut plantations, but mostly this element seems to be in sufficient supply.

Boron - The limited number of boron analyses showed generally adequate levels of this element.

A series of analyses were performed on wood and bark from six of the common tree species, for nitrogen only (Table 25). *Pisonia* and *Neisosperma (Ochrosia),* which occur mostly in the central parts of the islands away from the beaches, show higher levels of nitrogen in both bark and wood than the other species. The presence of better developed soils in the centers of the islands as well as more droppings of roosting birds may account for these higher levels. *Pandanus* wood also is fairly high in nitrogen, probably because much of the stem is living parenchymatous tissue. At least in the case of *Pisonia,* high leaf nitrogen levels correlate well with the high values in the wood and bark.

On the atoll substrates, varying from fresh deposits of sand to well developed soils in the centers of larger islands, it is not surprising to find evidence in the chemical analyses of much variability in the supplying capacity for the essential elements. For potassium, nitrogen, phosphorus, iron, and manganese there appear to be numerous locations where the supply of one or more of these elements is inadequate. Consequently, to encourage best plant growth, mineral fertilization is usually necessary.

Growth Response of Coconut to Fertilization

The Rongelap people planted many coconut seedlings in 1959-60 with aid from the Trust Territory agricultural officer, who arranged for seed nuts from Yap Island. In 1959 and 1961, various fertilizer treatments were made in several of these plantations. In 1961 and 1964, height growth measurements were made on a series of these plants. The results are given in Table 26.

Table 25. Mean Nitrogen concentrations (% of dry weight) in wood, bark, and leaves of woody plants of Rongelap Atoll

	Plant Tissue		
Species	Wood	Bark	Leaves
Cordia	0.10	0.45	1.92
Guettarda	0.11	0.54	1.36
Neisosperma (= *Ochrosia)*	0.18	1.04	—
Pandanus	0.20	0.46	—
Pemphis	0.09	0.46	—
Pisonia	0.60	1.52	2.16
Scaevola	0.08	0.47	1.29
Suriana	0.16	0.58	—
Tournefortia	0.12	0.66	1.39

Table 26. Height growth[1] of seedling coconuts with fertilization on Rongelap Atoll

	Pit 1		Swale		Kabelle	
Treatment	cm	%[2]	cm	%[2]	cm	%[2]
Control						
1	5	5	36	24	0 all died	0
2	20	18	51	33		
Multi-tracin	99	85	91	75		
Fe-tracin	58	62	89	62		
Fe-tracin & Cu, Mn, Zn NH_4 Phosphates	66	54	74	58		
Fe, P, NH_4 Cu Phosphates	86	73	97	58		
Fritted Trace Elements	46	33	69	50		
Combined Micro-Nutrients					56	196

[1] Pit 1 and Swale results are the average of 10 plants for the period 3/63 to 8/64. Kabelle Island results are averages of 15 plants from 3/61 to 8/64.

[2] Growth during period as percent of initial height

Clearly all fertilizer treatments increased growth above that achieved by the control plants, although *Fritted Trace Elements* appeared to be less effective than the others. It seems likely that the principal response was to iron, not only from the greening which was very apparent, but also *Iron-Tracin* alone gave good results and the application of additional elements along with *Iron-Tracin* did not improve growth. However, *Multi-Tracin* stimulated somewhat better growth than *Iron-Tracin* at Pit 1 (Rongelap Island), and combined micronutrients resulted in good responses on Kabelle Island. In view of the low manganese concentrations in the palm foliage (see Table 24), one could expect that the manganese in the multielement materials would be beneficial. In retrospect, combination of nitrogen fertilization with the micronutrient treatments probably would have increased the responses.

WATER RELATIONS

General Aspects

In the northern atolls of the Marshall Islands, annual precipitation is about 125 cm, with a pronounced dry season in the months of January to May. The mean annual temperature is 27C, with afternoon highs reaching over 30C. With the very porous coral sands as the rooting substrate, and with high evapotranspiration especially during the dry season, water stress is a major influence in the survival and growth of vegetation. This is attested to by the relatively sparse vegetation in the northern Marshall atolls in comparison with the lusher plant growth in the southern atolls such as Majuro. Salinity in the atoll environment adds to the water stress through osmotic effects. This influence is always present, but becomes extreme during storms, with blowing of salty spray over the plants or with sea water even inundating lower lying areas. Thus all species which grow on these islands have some tolerance to salinity, and those which inhabit the beach and sand spit areas have to be very salt tolerant. An indirect indication of this tolerance is the accumulation of sodium in the leaves (see Tables 21 through 24). This ability to absorb sodium, then translocate it to the shoot system, allows these plants to build up higher osmotic concentrations in the leaves than can plants which do not translocate sodium readily.

Despite the considerable salt tolerance of *Scaevola*, its leaves often showed temporary wilting in the warmest part of the day, even though humidity seemed high. Perhaps rise in leaf temperature, which would increase transpiration, coupled with unfavorable osmotic relationships in the soil which would decrease water absorption, combine to induce water deficits. Mid-day temporary wilting was seen often in *Pisonia* as well.

As discussed earlier, one feature of atoll islands, especially larger ones, is the presence of a lens of fresh or brackish water in the coral sand matrix a meter or two below the surface and extending downward as much as several meters. There is good reason to believe that plants derive much of their water from such lenses, especially during the dry season (see below).

In the following sections, some data are presented on the ground waters and the growth of plants in strand sites and in salinized solutions in the greenhouse.

The Salinity and Ionic Composition of Ground Waters

Galvanized steel pipes (1.25 cm interior diameter) with wedge-shaped perforated points were driven into the soil at numerous locations on Bikini Atoll and on Rongelap, Eniaetok, Kabelle, and other islands of Rongelap Atoll. Depth of penetration commonly needed to be 1.5 to 4 m to reach ground water. A plastic tube was fed into the pipe down into the water, then a hand-operated suction pump used to obtain a sample of the water. The pHs of these samples commonly were 7.5 to 8.5. Electrical conductivity was read on the samples, some values for which are given in Table 27. Most of the pipes were driven at or near soil pits, most of which can be located on the maps of Rongelap and Kabelle Islands (Figures 5 and 6). With the electrical conductivity of sea water (about 50 mmhos/cm) as a reference, one can see that ground waters vary from the same concentration as sea water down to only slightly brackish waters characteristic of an ideal "fresh water lens." Even in the interiors of islands the ground water may be 1/4 to 1/2 as concentrated as sea water. Plants can nonetheless absorb water from solutions this strong (Léskó, 1968; Walker and Gessel, 1991).

For some of the ground water samples from Rongelap and Bikini atolls, analyses were made of the major cations. These data are given also in Table 27. Although sodium is the dominant cation, appreciable concentrations of calcium, magnesium, and potassium are present, similar in proportion to those in sea water.

Osmotic Relations of Strand Species

These aspects were studied by Walker and Gessel (1991). They determined osmotic potentials (Ψ_π) and sodium contents of leaf samples collected in the field on Rongelap Atoll, used ground water data such as those presented in Table 27, measured electrical conductivities also of soil solutions, and grew several woody atoll species in the greenhouse in culture solutions with varying levels of added salt. The mean Ψ_π of the field-collected leaves ranged from -1.9 to -3.1 M Pascals, compared with that of seawater at -2.7 M Pa. Sodium contents of the leaves were high, commonly being 1 to 3% of the dry weight. Ground water conductivities mostly ranged from 16 to 50 mmhos/cm (equal to about -0.86 to -2.7 M Pa Ψ_π), but saturation extracts of soils were only moderately saline [equivalent to Ψ_π values of about -0.05 to -0.07 M Pa]. In culture solutions, seedlings of four shrubby species (*Cordia subcordata, Guettarda speciosa, Scaevola sericea, and Tournefortia argentea*) and a local variety of squash (*Cucurbita pepo L.*) all grew well at solution Ψ_π of -0.28 MPa, but were depressed to about 50% yield at -0.42 M Pa. The woody species declined to about 10-20% yield at -1.4 M Pa, and grew only a little at -2.8 M Pa (a solution equal in Ψ_π to that of sea water).

Walker and Gessel found in their greenhouse study that seedlings of several species which occur on or near atoll beaches can endure exposures of the roots to osmotic

Table 27. Ionic composition of Rongelap and Bikini Ground Waters (including a comparison with sea water)

Sample	pH		Conduct.	Ionic Concentrations (mEq/L)							Na^+ – %
	Field	Lab	(mmho/cm)	Ca^{++}	Mg^{++}	K^+	Na^+	Cl^-	$SO_4^=$	HCO_3^-	of sea H_2O*
Sea Water											
Rongelap	8.0		50.0	-	-	-		-	-	-	-
Friday Harbor, WA			66.2	18.6	90.6	9.2		612	49.1	2.47	-
Standard*				20.6	108	10.0	473	551	56.8	2.36	100
Rongelap Atoll											
Pit 1	7.7	7.72	34.8	14.3	59.5	5.65	348	298	30.2	4.80	74
1a			43.3	14.1	59.6	5.62	-	370	30.4	4.83	-
1b			34.6	14.2	60.1	5.83	-	289	31.0	4.75	-
4	7.5	7.92	27.9	16.6	46.6	4.44	-	232	22.3	7.02	-
4x		7.90	25.2	15.7	42.4	4.23	-	204	-	6.90	-
5	7.5				45.6	4.13	268	210	21.4	7.51	57
7		8.0	26.9	19.6	45.2	3.52	-	220	21.4	12.2	-
7x		7.82	24.0	16.1	40.5	4.05	-	208	-	8.90	-
12		7.88	37.7	18.3	59.8	6.59	-	315	31.5	6.21	-
22	7.9		12.7	-	-	-	-	-	-	-	-
23	7.9	8.20	25.6	13.9	41.8	4.05	-	218	-	5.76	-
27		7.40	14.2	7.54	22.5	2.49	-	123	-	4.33	-
Bikini Atoll											
Aerokoj (Airukiiji)			3.14	3.25	6.58	0.54	20.9	-	-	-	4.4
Nam (Pit 17)			7.25	6.00	13.4	1.59	52.2	-	-	-	11
New Tower 1 }Bikini			10.4	8.70	22.4	1.84	104	-	-	-	22
New Tower 2			11.1	8.15	24.0	1.76	104	-	-	-	22
Bwikor (Yurochi) (surface pond)			23.4	8.95	42.4	4.09	276	-	-	-	58
Eneu (Camp Blandy)			27.8	13.5	56.2	3.53	284	-	-	-	60

* From *Handbook of Biological Data*, William S. Spector, Ed., W. B. Saunders Co., N.Y. 1956

concentrations equivalent to that of sea water, but do not grow much at such high salinity. Nonetheless these species often grow well in nature close to both the lagoon and seaward shores. Ground waters in such locations are usually considerably less saline than sea water and the plants have extensive root systems penetrating to appreciable depths. These strand species can tolerate the salinity of most of the ground waters and probably absorb much water from them, especially during the dry season.

GENERAL ATOLL ECOLOGY

INTRODUCTION

Some time ago Fosberg summarized the nature of the Pacific atoll vegetation (Fosberg, 1953) and recently he wrote a description of the vegetation of Bikini Atoll for the Bikini Atoll Rehabilitation Committee (Fosberg, 1988).

The following sections are based on observations made at Rongelap and Bikini Atolls during the period 1958-64, made by Ralph Palumbo, Edward Held, Stanley Gessel and Richard Walker. Our observations were generally in good agreement with those of Fosberg (1953, 1988).

PLANT COMMUNITIES

Kimmel (1960) described seven plant communities occurring in the northern half of Rongelap Island (Figure 13). His terminology will be followed here with minor exceptions. The communities are named for the most conspicuous or abundantly occurring genus. The community names are: I *Suriana* Society, II *Scaevola-Guettarda* Community, III Coconut Grove Community, IV *Pisonia-Tournefortia* (*Messerschmidia*) Community, V *Ochrosia* Community, VIII Mixed Forest, and IX Coconut Plantation Community, and we have added the *Cordia* Community and the *Pemphis* Community here. Increased coconut planting has decreased the areas of these plant communities somewhat, but all could be recognized as of February 1986. Since the island has been mainly uninhabited since that time, there has probably been substantial regrowth of native woody species.

Scaevola-Guettarda Community. *Scaevola sericea* generally constitutes about 80 percent of the vegetation in the *Scaevola-Guettarda* community, but commonly occurs in dense, pure stands. This is the most prevalent community along the beaches where, typically, it is wedge-shaped, since the shrubs grow taller with increasing distance from the shoreline. Fingers of bare sand characteristically penetrate the community from its shoreward margin inland for as much as a few meters. In such openings herbaceous species are common: esp. a grass, *Lepturus repens*, a sedge, *Fimbristylis* sp. and a vine, *Triumfetta procumbens*. In some leeward areas, typified at Kabelle Island, the *Scaevola* community is open. The surface of the soil, almost pure sand in these areas, is covered with black algal crust and wherever one digs, the shrub roots are evident, apparently

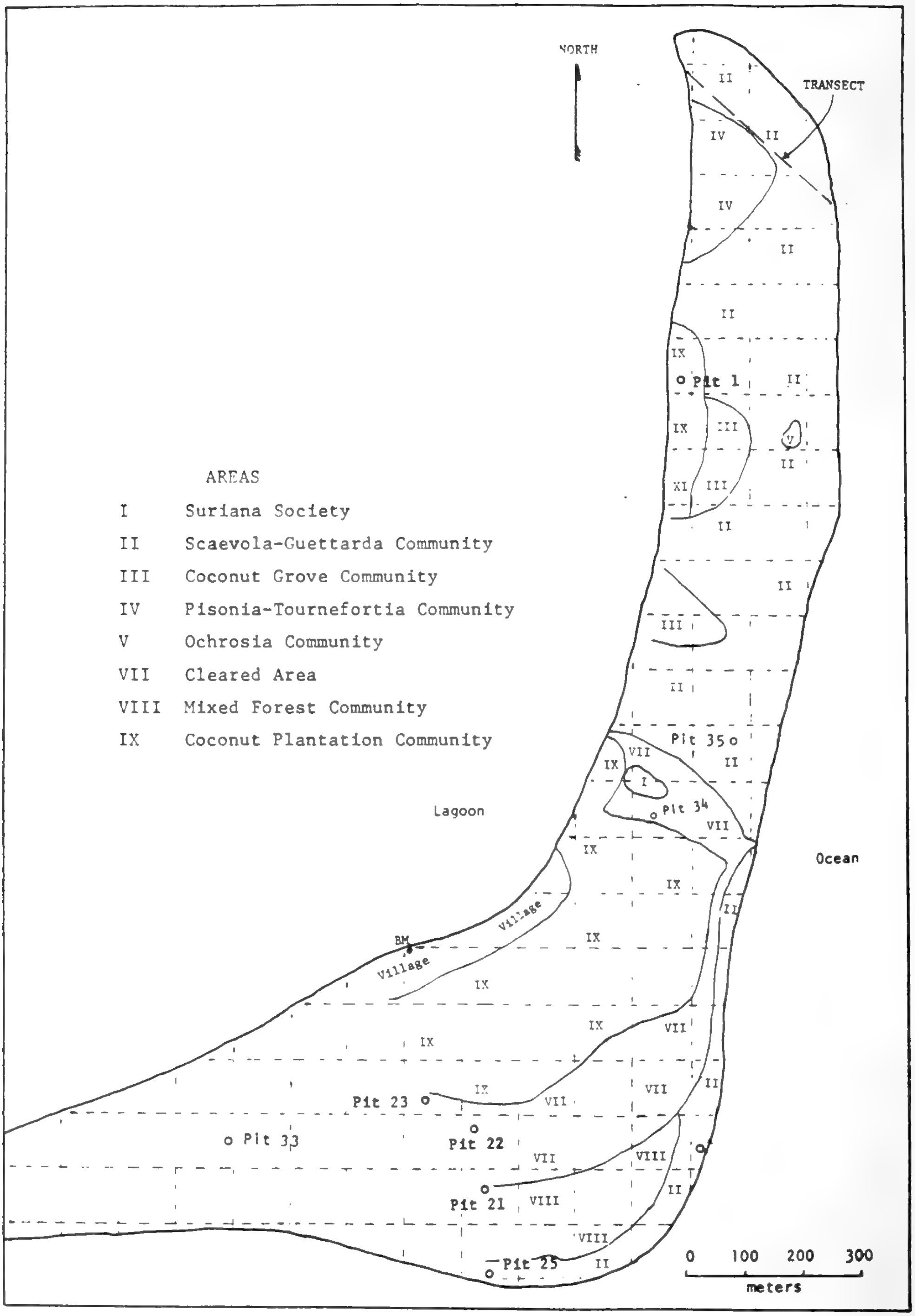


Figure 13. Vegetation Map of the Northeastern Part of Rongelap Island. [As charted in 1959 (after Kimmel, 1960); much altered by 1986]

utilizing the resources of the entire soil area. Occasionally, the shrubs have a yellow or pale orange cast when seen from a distance. Closer inspection shows the presence of *Cassytha filiformis* parasitizing the plants. The principal co-dominant, *Guettarda speciosa,* is found primarily on the leeward shores or in protected areas. Other associated species include *Tournefortia argentea, Pandanus* spp, the coconut, *Cocos nucifera, Terminalia samoensis* and *Morinda citrifolia.*

Suriana Society. Pure stands of *Suriana martima* form small communities along the windward shores of some islets. *Suriana* also occurs in the interiors of Rongelap, Lomuilal and Naen Islands, but only where there is evidence of overwashing with sea water. Severe dieback nearly always occurs in *Suriana* communities but its cause is not apparent, for while windblown sand is deposited along the bases of shrubs on the beaches, there is also dieback in the interior areas where there is no such accumulation and where, presumably, the effects of salt spray and wind are less severe than on the beach.

Pisonia-Tournefortia Community. *Pisonia grandis* is indeed well named; by atoll standards it is a tremendous tree rising upwards to as much as 20m and forming a dense closed canopy during the wet season. However, during the dry season, many leaves are shed so that the crowns become very thin. Although not as tall and often recumbent, scattered old specimens of *Tournefortia* are usually present also.

How this community starts is not known. It is generally associated with more fertile soils but scattered individuals of *Pisonia* do occasionally occur anywhere and the species readily reproduces by sprouting. The sticky fruits of *Pisonia* are sometimes seen attached to birds, and this is probably an important means of dispersal of the seeds.

A substantial part of our work on Rongelap Atoll was centered on Kabelle Island, the vegetation of which has been little disturbed by humans, since it is remote in the atoll, is visited only occasionally, and has only a few coconut trees. A depiction of the approximate distribution of vegetation on this island is given in Figure 14. A feature of special interest is the presence of very large and obviously quite old *Tournefortia* trees in the central part of island . Trunk diameters of such trees, which are often partially or completely recumbent, may be up to almost one meter. One might hypothesize that *Tournefortia* seedlings established on such an island when it was small and persisted as the island accreted and enlarged. *Tournefortia* seeds float in sea water and their germination is stimulated by this soaking (Léskó and Walker, 1969). Eventually *Pisonia* would establish in the central part of the larger island, but the old *Tournefortia* would still be present. Such a scenario seems to fit with the presence of those old trees among the *Pisonia* on Kabelle Island. Age of trees in a tropical environment, where annual rings are lacking or undependable, is difficult to ascertain. However, we know that medium-sized *Tournefortia* trees on Kabelle Island changed only slowly over the 28 year span from 1958 to 1986 (Table 29).

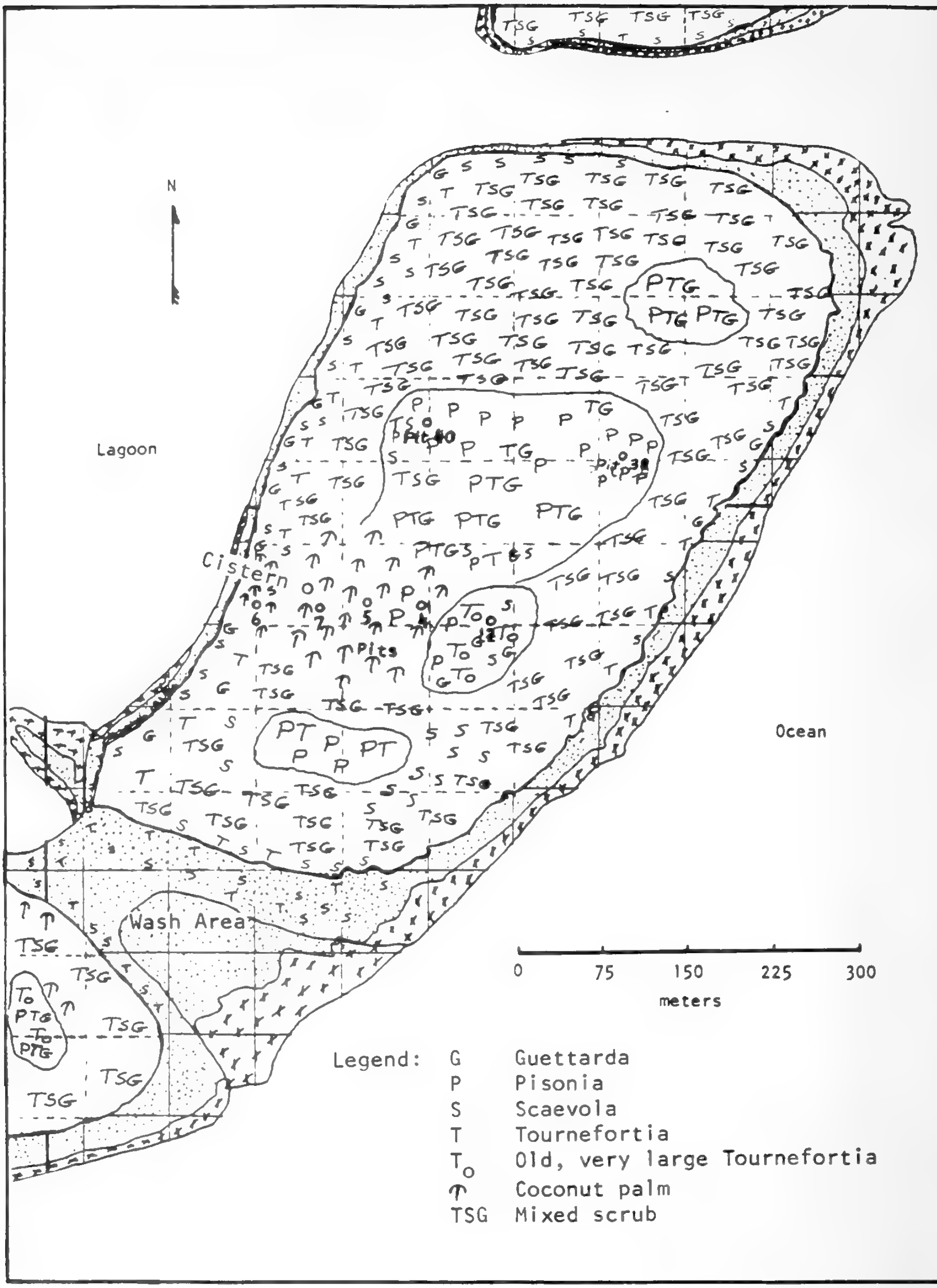


Figure 14. Map of Kabelle Island, Rongelap Atoll, showing distribution of vegetation (Note: Charted in 1959, but little changed in 1986).

The wood of *Pisonia* is soft and porous and, presumably, solitary trees are easily blown down during storms. Such a fallen trunk initiates roots and puts up shoots which eventually dominate the area, forming dense stands with a ground cover of *Boerhaavia tetranda* and *Boerhaavia diffusa*.

The best soils at Rongelap are found in the *Pisonia* communities. Litter deposition is heavy and a thick humus layer often develops. The stands are favorite nesting areas for fairy and noddy terns. It was conservatively estimated (by the late Dr. Frank Richardson) that some 1,400 terns, frequenting and nesting in a *Pisonia* community of about 0.25 hectare in area on Kabelle Island, consumed about 48 tons of fish per year. The birds thus bring nitrogen, phosphorus, and other nutrients from the sea to the islands. The better coconut groves (on the larger islands) appear to be in areas which were once *Pisonia* groves, but with the fertility of the soil diminished by the agricultural practices used.

Ochrosia Community. *Ochrosia* (now named *Neisosperma oppositifolia*) forms a community of a few trees at Naen Island and there were several small communities at Rongelap Island in 1959. The latter have meanwhile succumbed to clearing for the planting of coconut. In 1959, these small communities consisted of young trees 6 to 9 m tall, with large leaves forming a dense canopy. *Ochrosia* seedlings were abundant and, together with scattered *Scaevola* shrubs, formed a second layer 1.5 to 2 m high. The dominance of *Ochrosia* was complete and on Rongelap Island it was encroaching on an adjacent *Scaevola* community. *Ochrosia* forests composed of large trees growing in pure stands in areas other than Rongelap have been reported by Fosberg (1953).

Cordia Community. *Cordia subcordata* communities characteristically occur in boulder areas and are best developed on Rongelap Atoll at Mellu Island and Anielap Islet , where the canopy rises to obvious height. The bases of the *Cordia* trees may be up to almost a meter in diameter, and the trunks and branches grow at all angles, often close to the ground where boulders are found piled against their seaward side at Mellu Island. The appearance of the community is tangled and rugged. Occasionally, there is a *Pisonia* tree, but *Cordia* is clearly dominant and there is no ground cover.

Coconut Plantation Community. The trees are usually spaced 3 to 6 m apart in reasonably straight rows. As previously mentioned, beginning in the late 1950s, Trust Territory agriculturalists provided coconuts from superior trees of Yap Island. These coconuts were sprouted in nurseries at Rongelap; the seedlings were then transplanted to holes almost a meter deep, partially filled with coconut husks and other humus-producing material. In this method, as the trees grow, soil is gradually filled in around their bases, resulting in better root structure, greater productivity of the trees, and greater resistance to wind throw than is the case if nuts are planted more shallowly.

Coconut Grove Community. This consists of three layers: first, a canopy of coconut palm fronds, 10-13 m high, which is either continuous or broken, depending on the age and condition of the plantation; next, there is a layer from 1/2 to 4 m high, consisting of

coconut seedlings, a few *Pandanus* seedlings, and occasional *Pseuderanthemum atropurpurem* and *Clerodendron enerma* shrubs, *Tacca*, and occasionally, small *Morinda* trees. The third layer is the ground cover, which is varied and may be composed of grasses, (*Lepturus, Digitaria pruriens, Eleusine indica*), the sedge, *Fimbrystilis*, and scattered individuals of other herbaceous plants. Of the associated species in this community, *Pandanus* and *Tacca* are food plants and the fruit of a third, *Morinda*, is eaten by the pigs and allowed to grow to a limited extent throughout the plantation area.

There are at least three distinct types of *Pandanus* at Rongelap. One has edible fruit, a second has leaves which are especially prized for weaving fine quality mats, and a third, called wild *Pandanus* or erwan, has fruits which are edible but not desirable and leaves which are not particularly sought after for weaving. However, the leaves of all three types are used for making coarse mats and baskets. *Tacca*, or arrowroot, is conspicuous in the second layer of the community during the wet season and lends a noticeable seasonal aspect to the community since the leaves die down completely during the dry season. The shoots arise from corms forming a dense, luxuriant growth which completely shades the soil surface. Arrowroot corms provide the only source of locally-produced starch.

In general, the coconut plantation is an open, shaded community, both easy and pleasant to walk through. But these qualities remain only so long as the plantation remains under cultivation. If neglected for two or three years, the coconut plantation community becomes a coconut grove community, in which volunteer coconut seedlings along with *Pandanus* trees and a variety of native shrubs have invaded. In some areas, especially those cleared and burned, the grass *Lepturus* may form extensive stands.

Mixed Forest Community. The mixed forest community is composed of a variety of species, none of which is dominant. The canopy, rising up to 7 to 9 m, usually consists of *Pisonia*, coconut, *Terminalia* or *Cordia*, with *Morinda, Guettarda, Tournefortia*, and *Scaevola* forming the somewhat lower layers. The trees usually are clumps of a few coconut trees, or clones of *Pisonia*, *Scaevola*, or *Cordia*. The general aspect is one of a dense heterogeneous mixture of a number of species, with the canopy being the only distinct layer and with essentially no ground cover other than seedlings of the coconut and sprouts of the *Pisonia*. It is perhaps noteworthy that *Neisosperma (Ochrosia)* does not occur in the mixed forest communities.

Pemphis Community. Finally, there is a *Pemphis* community which was not described by Kimmel (1960) because it does not occur in the northern half of Rongelap Island. It is best developed on the leeward, lagoon shore of Mellu Island where *Pemphis acidula* grows among the boulders and beach rock high in the intertidal zone, occupying a position similar to that of *Suriana*, but growing to a height of 4 to 6 m. Both at Mellu and elsewhere, *Pemphis* trees can be seen standing in sea water at high tide. Rarely, small *Pemphis* groves occur inland, as does one in the narrow neck between Rongelap village and Jabwan on Rongelap Island, where there was very likely occasional inundation in the past.

In addition to those plants mentioned in discussing the plant communities, in the village area there is the breadfruit, *Artocarpus altilis,* and *Papaya carica,* the fruits of which are utilized as food. There are also ornamentals, which include the spider lily, *Crinum* sp., *Croton* sp., and *Achryanthes canescens.* Squash or pumpkin, as it is called locally, is planted in a few areas behind the houses.

A QUANTITATIVE DESCRIPTION OF THE *SCAEVOLA-GUETTARDA* COMMUNITY ON RONGELAP ISLAND (A study carried out by Dr. Mark Behan in 1959)

The purpose was to describe quantitatively the *Scaevola-Guettarda* (Sca, Gu) community with respect to the relative abundance of the species, the area occupied by each, and the total number of individuals per unit area. Also the homogeneity of the stand with respect to the distribution of the different species, and obtaining an index to predict future changes which may occur in the composition of the stand by focusing some attention upon the seedling population, were given some attention. (for methods see Phillips, 1959)

1) Location

This transect started in vegetation at the lagoon fringe about 100 m south of the northern tip of the island, then ran southeast for about 250 m to the seaward beach ridge (see Figure 13).

2) General Description of the Vegetation

The vegetation seemed typical of the *Sca-Gu* community, in which *Sca* predominates numerically, and the vegetation as a whole was dense and of an average height of about 3 to 4 m. The *Sca* appeared to be approaching maturity as judged by its height, stem size, bark thickness, and the number of sprouting old prostrate stems. Field notes describing the transect are as follows: "The transect covers what appears to be a mature *Sca-Gu* association in which the *Sca* is mostly shrublike, with several spreading branches at the base, about 4 m tall. The *Gu* is more arborescent and of about the same height. The canopy is continuous and composed predominantly of *Sca. Gu* occurs frequently as seedlings. In places a small pure stand of mature *Gu* may be seen, and in contrast to the *Sca,* the seedlings of *Gu* occur at several stages of maturity. *Sca* seedlings, although frequently seen, are conspicuous by the lack of seedlings taller than 10 cm. *Pisonia* (Pi) occurs as a mature tree at the beginning of the transect. *Pandanus,* Coconut, and *Tournefortia* were observed infrequently near the transect, but did not occur on it. *Gu* appeared to be spread farther apart from their neighbors than did *Sca,* and the ground beneath the crown of the more mature *Gu* was generally barren of plant life. This was not the case with *Sca,* as many seedlings of both *Sca* and *Gu* were often observed under the crown of *Sca.* Herbaceous cover was scant and consisted mostly of *Ipomoea, Triumfetta, Boerhaavia,* and *Tacca.*"

3) Quantitative Data

Methods: At 6 m intervals along the transect a station was established and a line was drawn at right angles to the direction of the transect. The species and distance to the nearest plant was recorded in each of the four quarters formed by these two lines according to the principles of the Quarter method. At each station a note was made of the cover directly over that point, the species and distance to the nearest seedling in any direction from that point, and the presence and species of the herbs in the vicinity of the station.

4) Results

Cover: At 14 stations the plant crown which covered the station was noted. At 11 stations (79%) *Sca* covered the station; at 2 stations (14%) *Gu* covered the station and in one instance (7%) *Pi* covered the station.

Calculated Values	Mature Plants				Seedlings			
	All	Sca	Gu	Pi	Sca	Gu	Pi	
Mean Distance: from the station to the nearest plant in each quarter								
Sum of distances	604	443.5	125.0	34.5	27.6	47.5	11.7	feet
Number of distances	105	83	15	6	10	14	2	
Mean distance	5.81	5.34	8.40	5.75	2.8	3.0	5.9	feet
Mean Area occupied by an individual	33.8	28.5	70.5	33.1	7.6	8.7	34.8	$feet^2$
Relative Density	100%	79.8%	12.8%	5.1%	38.5%	54.0%	7.5%	
Density or number of individuals per acre $\frac{43560}{d^2}$	1289*	1030*	165*	64*				
Relative Frequency		100%	46%	15%				

Relative Density: $\frac{\text{No. of points of occurrence of species "x"}}{\text{No. of points of occurrence of all species}} \times 100$

* = relative density X total number of individuals per acre

Relative Frequency: $\frac{\text{number of stations of occurrence of species "x"}}{\text{number of stations}} \times 100$

5) Analysis of Quantitative Data

The mean area calculations clearly show that the *Sca* forms a much more dense community than does *Gu*, which substantiates the field observations. Adequate data were not obtained to draw a conclusion of similar nature about *Pi*, since only six points included this species. The average mean area for all species indicates a very dense community, confirming the field observation. The mean area showed that each individual occupied a plot about 1.7 X 1.7 m.

The relative density data is interesting because it also quantitatively confirms the field observation that even though *Sca* may form the principle cover and number abundance of the community, *Gu* will probably become a more dominant species in time. This conclusion is reached by comparing the relative density of the mature plants with that of the seedlings. The data show that in the case of *Sca*, the mature plants comprise by far the majority of the mature vegetation. The seedling population, however, is dominated by *Gu*. In addition, very few *Sca* seedlings exceeded 10 cm in height, indicating a great deal of *Sca* seedling mortality. This was not the case with *Gu*, in which a continuous distribution of ages was noted. This is consistent with the known shade tolerance of *Gu* and shade intolerance of *Sca*, and the frequently encountered situation of *Gu* growing up through a crown of *Sca*.

The number of individuals per acre forms an index of the productivity of the land. It would be a much more valuable number if some idea of the average volume or weight or both of the species occupying this site were known.

The relative frequency is an expression of the dispersal of the various species throughout the area. As may be seen from the data, because of the abundance, *Sca* is thoroughly dispersed throughout the community, and *Gu* is more evenly dispersed than the general field impressions would lead one to think. A field impression indicated that *Gu* may occur often as a pure stand, or may be distributed in clumps or clusters; this impression is undoubtedly valid, but *Gu* also is fairly evenly distributed throughout the area as an individual as well. As one approaches the seaward beach area in this transect *Gu* is no longer encountered in the abundance found farther from the beach. If one were to recalculate the relative frequency of *Gu*, excluding the last 20 m of the transect, the relative frequency of *Gu* rises to 52%. *Gu* did not appear among the samples for the last 20 m of the transect, but was infrequently observed.

6) Summary

Measurements were made along a transect by use of the quarter method of a typical undisturbed *Sca-Gu*. The data gathered indicated:

1. The aerial cover and relative density of the population coincide, and the mature vegetation is composed predominantly of *Sca* (80%) and secondarily by *Gu* (13%). The condition in the seedling population is reversed, with *Gu* representing 54% of the see-

dling population and *Sca* comprising 38% of the seedling population. This observation, combined with the apparent high seedling mortality of *Sca* and the shade tolerance of *Gu* confirmed that this community will probably become more and more dominated by *Gu* in the future.

2. The average mean area indicated that the vegetation as a whole is quite dense. It also indicated that *Gu* occupied about twice the area per individual as did *Sca*. This confirms that *Gu* is more widely spaced than *Sca*, as may be observed in the field by shrub-like appearance and high density of *Sca*, and the more arborescent and widely spaced appearance of *Gu*.

3. The relative frequency of the species within the population indicated that *Gu* was fairly evenly dispersed throughout the community while *Pi* was clumped or clustered about a comparatively small area. This was substantiated by the field observation, as *Pi* was encountered only at the beginning of the transect.

4. Insufficient data was obtained to characterize the *Pi* community.

5. It was suggested that future work include some measure of the average weight or volume of the various species in the community. If this were known these measurements could be incorporated into a reasonably accurate estimate of the total production of the area.

WEIGHT OF VEGETATION (BIOMASS)

Total biomass production data are now commonly used to compare productivity of different ecosystems. Unfortunately, we were not able to secure much information of this kind on the various expeditions to the Marshall Islands. However, when vegetation clearing was taking place on Bikini Island in 1967 to prepare for the coconut plantation, records were taken as a *Scaevola* brush area was being cleared. Vegetation consisted mostly of *Scaevola*, but with some admixture of *Dodonaea*. A circular area was cleared and records of vegetation weight kept by different size circles from 29.2 m^2 to 262.7m^2 (Table 28). Litter on the soil surface was also collected and weighed separately. In this case, total above-ground biomass was about 9000 g/m^2 and litter about 1400 g/m^2. Litter weights under different species from various Rongelap Atoll islands are given in Table 9.

VEGETATION GROWTH RATES

The periodic visitor to this island environment gets the impression of relatively rapid establishment of plant cover even on severely disturbed areas. Great variation in the size of plants from one local environment to another is apparent, but with little information on reference ages it is difficult to establish rates of growth. Although our data are

limited, we established several plant measurement areas for both radial and height extension on different species, and made periodic measurements.

Radial Growth. Because *Pisonia* trees attain a greater size than any other vegetation and in places form a respectable forest cover we established measurement sequences in two different areas, both on Kabelle island. In both instances trees were identified by numbered tags placed at 1.4 m above the ground surface (breast height) and initial diameter taken at that point. One series near Soil Pit 12 was established in 1958 while the other at Pit 38 was set up in 1961. The trees were remeasured each time a visit was made to the area, with the last measurement in 1964. We found the localities on a return in 1986, but either identifying tags had been removed by other visitors or had been incorporated into the trees, so we were not able to identify the numbered trees. Results are presented in Table 30. These show considerable variation in individual tree growth. The Pit 38 area is a more uniform *Pisonia* forest area and with greater influence of nesting sea birds. Pit 12 is near the water cistern and more subject to human disturbance. Trees at Pit 12 averaged 0.39 cm diameter growth a year while those at Pit 38 averaged 1.32 cm/year.

We set up a similar study of *Tournefortia* trees on Kabelle Island during the period 1959 to 1961. Final measurements were taken in 1964 on most trees, but two of these were found in 1986 and remeasured. Up to 1964, diameter growth rates varied from 0.1 to 1.5 cm/yr with better growth on better soil (Table 29). The tree on the better soil (Pit 12) grew an average of 1.6 cm/yr through 1986, while on the young coral sand soil (Tree #25) growth though 1986 was only 0.7 cm/yr, even though it was a young healthy tree of only 2.5 cm diameter in 1959.

Height Growth. In order to evaluate height growth, a series of *Scaevola, Guettarda,* and *Tournefortia* plants were identified by numbered tags and initial heights taken from 1958 to 1961. These were remeasured at each visit to the island through 1964. We could only identify one plant for remeasurement in 1986. Results are given in Table 31. As with diameter, there is considerable variation in height growth within a species. This is probably related to the soil quality in which the plants are growing and exposure to wind. *Scaevola* plants averaged 21.4 cm/yr height growth, *Guettarda* 27.2 cm/yr and *Tournefortia* 16.4 cm/yr. *Tournefortia* #25 grew quite rapidly through 1964, while a younger plant, but slowed down as it grew older and much broader and averaged 15.8 cm/yr over a 28-year period. Many of the plants used in this study were growing on quite poor soils and exposed sites. The growth rates therefore probably represent the low end of the scale for annual height growth of these species, especially since Rongelap is one of the northern and thus drier atolls.

NATURAL AND MAN-MADE CHANGES IN THE VEGETATION

The buried horizons which are present in many of the soil profiles, especially those nearer windward beaches (see Figures 9 and 10), are convincing evidence of dramatic changes which have occurred in the vegetation in the past, presumably from wind and

Table 28. Air Dry Weight of Vegetation Components and Litter for Bikini Island Clearing Area (1967)

Area of Sample	*Scaevola*	*Dodonaea*	Total Vegetation	Litter
m^2	g/m^2	g/m^2	g/m^2	g/m^2
29.2	9,233	48.6	9,282	919
87.6	8,890	58.6	8,949	1,883
145.9	9,037	19.6	9,057	1,202
262.7	9,037	39.1	9,076	1,397

Table 29. Diameters (cm) and Diameter Growth Rate (cm/yr) of *Tournefortia* Trees on Kabelle Island, Rongelap Atoll

Tree No.	Location	Measurement Dates							Total Growth		Rate	
		3/59	3/61	9/61	3/63	8/63	8/64	3/86	to ‘64	to ‘86	to ‘64	to ‘86
						Diameter (cm)						
11	Pit 12	18.8	20.8	21.6	22.6	23.1	24.4	62.9	5.6	44.1	1.1	1.6
73	Wash area		20.8		20.8	20.8	21.0		0.3		0.1	
	Wash area		24.1		24.6	24.6	24.6		0.6		0.1	
41	Pit 38			17.0	18.5	18.8	20.3		3.3		1.1	
42	Pit 38			16.5	17.3	17.5	18.5		2.0		0.7	
43	Pit 38			18.8	20.8	21.3	23.4		4.6		1.5	
44	Pit 38			13.7	14.0	14.2	14.5		0.8		0.3	
45	Pit 38			16.8	16.8	17.3	17.8		1.0		0.3	
25	Wash area	2.5						22.6		20.1		0.7

Table 30. Diameter (cm) and Diameter Growth Rate (cm/yr) of Pisonia Trees on Kabelle Island, Rongelap Atoll

Location	Dates								
Tree No.	8/58	3/59	3/61	9/61	3/63	8/63	8/64	Growth 58-64	Rate
Pits 7-12				Diameter (cm)					
1	26.9	26.7	26.7	26.9	26.9	27.2	28.4	1.52	.25
2	25.4	25.4	26.2	26.4	26.9	26.9	27.4	2.03	.34
3	27.2	27.7	29.5	29.9	31.5	32.0	33.0	5.80	.97
4	40.1	40.1	40.1	40.1	40.1	40.1	40.6	0.51	.08
5	29.2	29.2	30.2	30.2	30.7	30.7	31.2	2.03	.55
6	34.8	34.8	34.8	34.8	35.0	35.0	35.3	0.51	.08
7	42.7	42.7	43.2	43.2	43.2	43.4	43.9	1.30	.21
8	47.0	47.0	48.3	48.3	48.8	49.3	50.5	3.80	.63
								Mean:	0.39
Pit 38								Growth 61-64	Rate
13				22.1	22.9	23.0	24.1	2.0	.67
14				31.0	32.5	33.0	35.6	4.6	1.53
15				15.7	18.3	18.7	21.8	6.1	2.03
16				19.6	20.8	21.3	22.6	3.1	1.02
17				24.4	25.2	26.2	27.9	3.6	1.20
18				22.1	25.0	25.9	28.2	6.1	2.03
19				32.2	33.5	33.8	35.6	3.3	1.10
20				33.3	34.5	34.8	36.3	3.1	1.02
								Mean:	1.32

Table 31. Height (cm) and Height Growth Rate (cm/yr) of Native Shrubs in the Wash Area on Kabelle Island, Rongelap Atoll

Tag No.	Measurement Dates 8/58	3/59	9/59	3/61	9/61	3/63	8/63	8/64	Total Growth	Rate
Scaevola					Height (cm)					
301	12.7	19.0	50.1	60.1	60.1	111.8	147.3	167.6	129.5	21.6
323	43.1		88.9	121.9	121.9	132.1	139.7	152.4	109.2	18.2
354	38.1		86.4	127.0	152.4	172.7	190.5	200.0	165.1	27.5
356	27.9	50.8	78.7	88.9	99.1	106.7	121.9	137.2	109.2	18.2
361	81.3		127.0	142.2	157.5	172.7	177.8	190.5	109.2	18.2
362	25.4		63.5	55.9	76.2	96.5	116.9	124.5	99.1	16.5
267	91.4	101.6	114.3	114.3	114.3	121.9	121.9	134.6	43.2	7.2
1				43.1	73.7	127.0	147.3	170.2	96.5	32.1
4				40.1	53.3	127.0	137.2	152.4	99.1	33.0
24					213.3	251.5	256.5		43.2	21.6
									Mean:	21.4
Guettarda										
21					289.6	312.4	340.4		50.8	25.4
23					190.5	221.0	248.9		58.4	29.2
									Mean:	27.3
Tournefortia										
345	25.4	27.9	43.2	50.8	61.0	71.1	91.4	124.5	99.1	16.5
372	55.9	55.9	66.0	91.4	101.6	121.9	129.6	157.5	101.6	16.9
319			76.2	88.9	94.0	101.6	111.8	114.3	38.1	9.5
328	17.8		43.2	55.9	63.5	86.9	76.2	76.2	58.4	11.7
341	83.8		86.4	104.1	111.8	124.5	132.1	142.2	58.4	9.7
368	142.2		149.9	162.5	165.1	182.9	182.9	195.6	53.3	8.9
370	91.4		101.6	111.8	121.9	129.5	139.7	144.5	53.3	8.9
2				50.8	73.7	106.7	130.0	130.0	56.3	18.8
3				76.2	104.1	152.4	170.2	185.4	81.3	27.1
25[1]	76.2				248.9	279.4	315.0	330.2	254.0	43.3
26					43.2		60.1	73.7	30.5	10.2
22										
									Mean:	16.5

[1]This plant was identified and measured on 2/86 with height of 518.2 cm and growth rate of 15.8 cm/yr for 28 yrs.

water of typhoons. Before man inhabited these atolls, and before copra production was an economic enterprise, the reasonably well developed soils in the centers of the larger islands are believed to have supported good stands of *Pisonia grandis* with some older *Tournefortia*, with a band of *Scaevola-Tournefortia-Guettarda* scrub along the beaches (Fosberg, 1949). With the development of copra production during the last 100 years, much of the *Pisonia* as well as a good deal of the scrub which is not too near the beaches has been replaced with coconut palms. This replacement involved considerable burning of the native vegetation.

The atomic weapons testing program on Enewetak and Bikini Atolls destroyed most of the palms and native vegetation on affected islands. Recovery of plants following a nuclear detonation on Enewetak Atoll was described by Palumbo (1962). Likewise rather rapid regrowth of native species after clearing for testing operations or from detonations on Bikini Atoll was documented by Gessel and Walker (1987).

As mentioned earlier, in the late 1950s and early 1960s, the Rongelap people aided by agricultural officers of the Trust Territories of the Pacific Islands, cleared scrub and planted many coconut seedlings of a strain from Yap Island. Likewise they replaced quite a few old coconut trees with seedlings of this strain, which is known to be quite productive. On Enewetak and Bikini Atolls, rehabilitation programs sponsored by the Trust Territories and the U.S. government in the late 1960s and early 1970s involved removal of testing debris, clearing of much of the centers of the larger islands, and the planting of coconuts. However, the lack of people living on Bikini and caring for the coconut groves has allowed native scrub and volunteer coconut seedlings to encroach on the groves. The move of the Rongelap people to Kwajalein Atoll in 1985 has permitted similar overgrowing to begin on Rongelap. Some photographs depicting these changes are included in Gessel and Walker (1987).

CONCLUDING REMARKS

In this bulletin, we have presented a substantial amount of data on the soils, plants, and ecology of atolls located in the Northern Marshall Island group--Rongelap, Bikini and Enewetak. Almost all of this information came from unpublished field records and laboratory analyses, graduate student theses, or other unpublished materials in our files. Reference has been made to published works by other workers and by our own group, some of which are reports which received limited distribution. We would appreciate readers informing us of relevant published or unpublished studies which we have overlooked. Also, we welcome correspondence with anyone interested in more detail concerning methods or observations.

Obviously, many of the results contained in this publication are fragmentary or incomplete. However, this will perhaps indicate the paucity of information on atoll soils and vegetation, and we hope stimulate other studies in this fascinating environment.

LITERATURE CITED

Baker, G. 1959. Key to the land plants of Rongelap Atoll. Laboratory of Radiation Biology.University of Washington, Seattle. 28 pp.

Billings, R.F. 1964. A description of nitrogen and phosphorus distribution in some Rongelap Atoll land ecosystems. M.S. Thesis, University of Washington, Seattle. 66 pp.

Chakravarti, D. and E.E. Held. 1961. Chemical and radiochemical composition of the Rongelap diet. J. Food Sci. 28:221-228.

Cole, D.W., S.P. Gessel, and E.E. Held. 1961. Tension lysimeter studies of moisture movement in glacial till and coral atoll soils. Proc. Soil. Sci. Soc. Amer. 25:321-325

Dible, W.T., E. Truog, and K.E. Berger. 1954. Boron determination in soils and plants. Analyt. Chem. 26:418-421.

Donaldson, L.R. et al. 1955. A radiological study of Rongelap Atoll, Marshall Islands, during 1954-55. UWFL-42, Laboratory of Radiation Biology, University of Washington, Seattle. 66 pp.

Fosberg, F.R. 1949. Atoll vegetation and salinity. Pacific Sci. 3:89-92.

_____. 1953. Vegetation of Central Pacific Atolls, a brief summary. Atoll Res. Bull. 23. 26 pp.

_____. 1954. Soils of the Northern Marshall Atolls, with special reference to the Jemo series. Soil Sci. 78:199-207.

_____. 1988. Vegetation of Bikini Atoll, 1985. Atoll Res. Bull. 315. 28pp.

_____. 1990. A review of the natural history of the Marshall Islands. Atoll Res. Bull. 330. 100 pp.

Fosberg, F.R. and D. Carroll. 1965. Terrestrial sediments and soils of the Northern Marshall Islands. Atoll Res. Bull. 13. 156 pp.

Gessel, S.P. and R.B. Walker. 1987. Marshall Island vegetation and the United States nuclear weapons program. Univ. Wash. Arbor. Bull. 50(1):20-24 and 50(3): 18-23.

Held, E.E. 1963. Qualitative distribution of radionuclides at Rongelap Atoll, pp. 167-169 in Radioecology, (Schultz and Klement, eds.), Reinhold Publ. Cp., N.Y.

Held, E.E., S.P. Gessel, and R.B. Walker. 1965a. Atoll soil types in relation to the distribution of fallout radionuclides. UWFL-92, U.S. Atomic Energy Commission, Division of Tech. Information (Biology and Medicine TID-4500).

Held, E.E., S.P. Gessel, L.J. Mattson, and R.F. Billings. 1965b. Autoradiography of sectioned soil cores. Proc. Symposium on Radioisotope Measurement Techniques in Medicine and Biology, IAEA, Vienna, Austria. 14 pp.

Jackson, M.L. 1958. Soil chemical analysis. Prentice-Hall, Inc., Englewood Cliffs, NJ. 498 pp.

Jenny, H., J. Vlamis, and W.E. Martin. 1950. Greenhouse assay of fertility of California soils. Hilgardia 20:1-8.

Kenady, R.M. 1962. The soils of Rongelap Atoll, Marshall Islands. M.S. Thesis, University of Washington, Seattle. 76 pp.

Kimmel, J.D. 1960. Plant communities of the northeastern half of Rongelap Island, Rongelap Atoll, Marshall Islands. M.S. Thesis, Ohio State University, Columbus.

Lésk6, G.L. 1968. Some ecological aspects of coral atoll beach colonization by *Messerschmidia* and *Scaevola.* Ph.D. Dissertation, University of Washington, Seattle. 210 pp.

Lésk6, G.L. and R.B. Walker. 1969. Effect of sea water on seed germination in two Pacific atoll beach species. Ecology 50:730-734.

Morrison, R.J. 1990. Pacific Atoll Soils: Chemistry, Mineralogy and Classification. Atoll Research Bulletin No. 339. 25 pp.

Nelson, V.A. et al. 1977. Radiological survey of plants, animals and soil at Christmas Islands and seven atolls in the Marshall Islands; Progress Report for 1974-1975. NVO-269-32, Nevada Operations Office, U.S. Energy Research and Development Administration. 69 pp.

Olsen, S.R. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Dept. Agric. Circular 939.

Palumbo, R.F. 1961. The difference in uptake of radioisotopes by marine and terrestrial organisms. Recent Advances in Botany (U. of Toronto Press), Sect. 12:1367-1372.

_____. 1962. Recovery of the land plants at Eniwetok Atoll following a nuclear detonation. Radiation Botany 1:182-189.

Phillips, E.A. 1959. Methods of Vegetation Study. Henry Holt and Co., New York. pp. 43-45.

Porter, S.C. 1966. Geomorphology of Windward Islands, Rongelap Atoll, Marshall Islands. Proc., Cordillerian Sect., Geol. Soc. Amer., Reno, Nevada, Abst. (ms. 21 pp. typescript).

Robison, W.L., C.L. Conrado, and W.A. Phillips. 1987. Enjebi Island Dose Assessment. UCRL-53805, Lawrence Livermore National Laboratory, 57 pp.

_____. 1991. Updated Dose Assessment for Rongelap Island. UCRL-LR-10736, Lawrence Livermore National Laboratory (in press).

Sandell, E.B. 1959. Colorimetric determination of traces of metals. 3rd Ed. Intersci. Publ. NY. 1032 pp.

Stone, E.L., Jr. 1951. The soils of Arno Atoll, Marshall Islands. Atoll Res. Bull. 5:1-56.

_____. 1953. Summary of information on atoll soils. Atoll Res. Bull. 22. 7 pp.

Taylor, W.R. 1950. Plants of Bikini and other Northern Marshall Islands. University of Michigan Press, Ann Arbor. 227 pp.

Walker, R.B., E.E. Held, and S.P. Gessel. 1961. Radiocesium in plants grown on Rongelap Atoll soils. Recent Advances in Botany, Section 12:1363-1367.

Walker, R.B. and S.P. Gessel. 1991. Osmotic relations of some plants of the Northern Marshall Islands. Pacific Sci. 45:55-62.

Welander, A.D. et al. 1966. Bikini-Eniwetok Studies. 1964. Part I. Ecological Observation, 277 pp. and Part II. Radiological Studies, 163 pp. UWFL-93, Laboratory of Radiation Biology, University of Washington, Seattle.

ATOLL RESEARCH BULLETIN

NO. 360

OCCURRENCE OF PHOSPHATE ROCK AND ASSOCIATED SOILS IN TUVALU, CENTRAL PACIFIC

BY

K. A. ROGERS

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

OCCURRENCES OF PHOSPHATIC ROCK AND ASSOCIATED SOILS IN TUVALU,CENTRAL PACIFIC

by

K.A. RODGERS

Abstract:

Phosphatic limestones and associated soils occur on eight of the nine islands of Tuvalu, central Pacific. Deposits range from gram-size to >500,000 tons. Carbonate hydroxyapatite, dahllite, forms crustose cement about calcareous bioclasts which it sometimes replaces. Precise genetic relationship of rock to soil is unclear. Consolidated rock occurs as hardpan within phosphatic soil profiles, with unconsolidated phosphatic layers above and below. Phosphatization has occurred either as a continuous or episodic process within the vadose zone for at least 4000 years. Present outcrops are exhumed accumulations of apatite formed in vadose zones corresponding to earlier, higher sea levels. A geobotanical relationship between the Tuvalu phosphate deposits and *Pisonia grandis* can not be sustained on present evidence and the tree should not be regarded as a geobotanical indicator today.

INTRODUCTION

Phosphatic limestones and associated soils occur on at least eight of the nine islands of Tuvalu, central Pacific. They range from slight phosphate crusts affecting no more than a few grams of limestone to deposits of >500,000 tons. As with similar low island occurrences, the Tuvalu phosphates are distinct from the massive deposits found on raised atolls and islands such as Ocean Island and Nauru; the two groups differing in occurrence, texture, mineralogy and chemistry (cf. Altschuler, 1973; Stoddard and Scoffin, 1983).

Recent studies in Tuvalu have yielded new information concerning the phosphatic limestones of all islands. Much of this new data is not widely available, existing in unpublished files and limited circulation, mimeographed reports. A summary of some of this information has been given by Rodgers (1989a) and it is proposed to provide here detailed descriptions of the various occurrences along with observations on the present geobotanical relationships of the deposits with *Pisonia grandis* in Tuvalu.

Department of Geology, University of Auckland
Private Bag, Auckland, New Zealand

Manuscript received 30 September 1988; revised 16 July 1991

TERMINOLOGY

Two types of "guano" phosphates have been identified on low islands and atolls (Hutchinson, 1950; Tracey, 1980):

(i) *phosphatic* or *ancient guano* which was the primary target of the nineteenth century guano miners. This is regarded as avian guano which has lost its volatiles and is found primarily on arid islands in the equatorial dry belt which receive less than 1000 mm of rain per year;

(ii) *cemented,* or *atoll phosphate* or *crust guano* - a honey brown phosphate which cements and replaces carbonate sand and gravel of the atolls. It is more widespread than phosphatic guano and occurs on both wet and dry islands, being common on those which receive between 2000 and 4000 mm of rain.

The relationship between the two types is not clear cut and the two may not be discrete (cf. Altschuler, 1973; Stoddart and Scoffin, 1983).

All Tuvalu phosphate deposits described to date belong to the second category but, as an avian origin for the Tuvalu deposits has not been demonstrated, terms which have genetic connotations, or which have been used with such connotations, will be avoided. Where a general term is required, the descriptive *crustose phosphate, phosphatic crust,* or *phosphatic limestone* will be used with no origin implied or assumed.

The term *phosphorite* (cf. McConnell, 1950; American Geological Institute, 1974) is inappropriate for most of the Tuvalu phosphate-bearing rocks. Few are composed essentially of apatite or other calcium phosphate. Nor does *phosphatite* (Slansky, 1980) apply to the majority. The modal per cent of phosphate varies widely from slightly phosphatized limestones to rocks which contain over 50% collophane. In only a few rocks does P_2O_5 exceed 18%, corresponding to 50 wt% carbonate-apatite. Calcium carbonate is the dominant species of most specimens examined. As such, terms such as *phosphatic limestone* or *phosphatic biocalcarenite* and *phosphatic biocalcirudite* (cf. Scolari and Lille, 1973; Slansky, 1980) are most appropriate.

The primary phosphate mineral found in the Tuvalu deposits is dahllite, carbonate hydroxyapatite (Rodgers, 1987, 1989a,b).

McLean *et al.,* (various dates) used the soil classifications and terminology of FAO-UNESCO *Soil Map of the World* (1974, 1978) to describe and map the soils of Tuvalu. The same nomenclature is followed here; the dominant soil types being Calcaric Regosols (Rc): very weakly developed soils on coral sand and rubble. Variations exist according to substrate grain size, depth of soil cover, presence of indurated layers, salinity and alkalinity. Phosphatic soil is one of three minor types.

It should be noted that the relationship of phosphatic soil to unconsolidated phosphatized sediment, and to cemented phosphate rock is such that any distinction between soil and rock may be artificial. Many of the soils described by pedologists in Tuvalu are the same materials which geologists have characterized as unconsolidated sediments and sedimentary rocks. Thus the "phosphatized sands" described and mapped by White and Warin (1964) are the "phosphatic soils" of McLean *et al.,* (various dates) and, insofar as the "phosphatic soils" contain cemented horizons, they are synonymous in part with Radke's (1986) "phosphatic limestones." No attempt has been made to map soil and rock as physically separate entities by any field worker in Tuvalu.

TUVALU - HISTORY OF RESEARCH

Tuvalu consists of nine small atolls and reef islands situated between 5° and 10.5°S latitude and 176° and 179.8°E longitude. From north to south the islands are Nanumea, Niutao, Nanumaga, Nui, Nukufetau, Vaitupu, Funafuti, Nukulaelae and Niulakita. The roughly linear archipelago is part of the Ellice-Gilbert-Marshall chain (cf. Morgan, 1972) and is the surface expression of thick carbonate carapaces draped over extinct volcanic mounds (Gaskell, Hill and Swallow, 1958). No part of any island exceeds 8 m elevation above sea level. Volcanic rocks dredged from the flanks of Niulakita are Cretaceous (Duncan, 1985).

Crustose phosphate deposits were exploited from Niulakita between 1899 and 1902 (Cochet, 1900; Becke, 1906). Small phosphate occurrences were described from the islets of Amatuku and Fongafale in reports of Royal Society expeditions conducted in 1896, '97, '98, concerned with deep drilling operations on Funafuti (Cooksey, 1896; Judd, 1904; Sollas, 1904). None of these deposits merited mention in Hutchinson's (1950) comprehensive review, and following the fall of major Pacific phosphate islands to the Japanese in World War II, the Ellice/Tuvalu occurrences were discounted as an alternative source of supply (Archives, High Commissioner, Western Pacific).

As part of a general assessment of the phosphate resources of the western Pacific by the Australian Bureau of Mineral Resources, White (in White and Warin, 1964) visited all islands of Ellice/Tuvalu except Niulakita whose deposits he believed to be exhausted. He reported new findings of crustose phosphate from Nui (3000 tons), Nukufetau (5000-10000 tons) and Vaitupu (10000 and 25000 tons) all in the range 10-20% P_2O_5 (cf. Warin, 1968). It is these deposits which are figured in reviews of Pacific phosphates (e.g. Cook, 1975; Lee, 1980; Aharon and Veeh, 1984; Cullen, 1986). White also noted a number of minor occurrences of phosphatic limestones throughout the archipelago.

A 1976, pre-independence report on prospects for agricultural and industrial development in the group by U.K. Ministry of Overseas Development included the first

TABLE 1. Summary of Climatic Data for Islands of Tuvalu

Island	Lat.	Long.	Annual rainfall (mm)			Temperature		
						mean daily		monthly mean
			max	mean	min	max	min	
Nanumea	5°40 S	176°06 E	4195	2733	953	29.9-30.8	24.9-25.3	27.5-28.1
Niutao	6°06 S	177°20 E	4163	2707	1109	29.9-30.6	24.9-25.3	27.5-28.1
Nanumaga	6°18 S	176°20 E	3847	2618	1243	29.9-30.6	24.9-25.3	27.5-28.1
Vaitupu	7°30 S	178°41 E	4257	3046	1872	30.2-31.1	24.8-25.4	27.6-28.1
Nui	7°13 S	177°09 E	4621	3172	1699	30.2-31.1	24.8-25.2	27.6-28.1
Nukufetau	8°00 S	178°29 E	4379	2810	1734	No temperature data available		
Funafuti	8°31 S	179°12 E	6770	3469	2225	30.2-31.1	25.0-25.5	27.7-28.2
Nukulaelae	9°22 S	179°50 E	4759	3240	2062	No temperature data available		
Niulakita	10°47 S	179°28 E	4738	3472	2577	30.9-31.8	24.4-25.0	27.8-28.5

description of the phosphatic rock of Niulakita (Flynn and Makin, 1976) but lacked essential geological detail.

The most significant contribution to understanding the extent of the Tuvalu phosphates resulted from land resource surveys prepared by Professor Roger McLean and co-workers for the United Nations Food and Agricultural Organization. Reports on each island include large scale maps showing geomorphic zones, soils and vegetation. These provided the first scientific cartography of Ellice/Tuvalu since the Royal Society Report of 1904 which was confined to Funafuti. Numerous soil profiles are documented, along with chemical and physical parameters. Copies of these reports are not widely available. The island descriptions presented below draw heavily on McLean's maps and data for seven of the islands. A partial report on Vaitupu was available in draft form only. No similar survey of Funafuti had been prepared at the time of writing.

Several investigators have looked for deposits of phosphates beneath the lagoon and reefs of the group: Warner and Rossfelder (1978) at Nanumea, Nanumaga, Nui and Vaitupu, Sahng-Yup (1981) at Funafuti and Radke (1985, 1986) at Nukufetau. No such deposits have been found but Radke's reports contained some petrographic detail of samples taken from terrestrial outcrops. Rodgers (1987, 1989a,b) identified the principal phosphate mineral present in Tuvalu as dahllite and found whitlockite in indurated surface outcrops.

Climate is regarded as exercising an important role in the occurrence of low island phosphates (Hutchinson, 1950: Tracey, 1980). The summary of temperature and rainfall data of Table 1 comes from sources given in Rodgers and Cantrell (1987).

Geographic names used on each island have varied over the years, as has their spelling. Those given here are current local usage. Former names are sometimes shown in brackets.

NANUMEA

Nanumea is a crescent shaped atoll with a broad apron reef and a comparatively small, shallow lagoon (Fig. 1). One horn of the crescent is aligned westnorthwest and contains the major islet of Lakena which is approximately 2.3 km x 800 m across and covers 119 ha. The second horn trends southwest and is dominated by the large, pincer-shaped islet of Nanumea proper (223 ha) with its associated smaller, oval companion, Temotufoliki (23 ha). Nanumea islet is about 6 km long and 900 m wide across the base of the pincers. The eastern lagoon obtrudes for some 3 km within these pincers.

White (in White and Warin, 1964) found only a few broken blocks and fragments of phosphatized sand close to the small freshwater pond on Lakena. However, McLean,

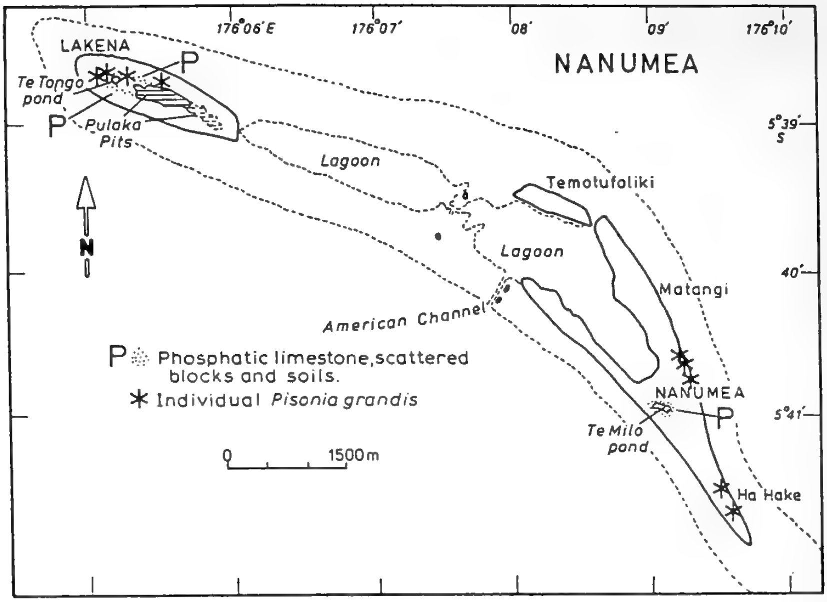


FIG. 1. Locality map, Nanumea. After McLean, Holthus, Hosking and Woodroffe (1986a).

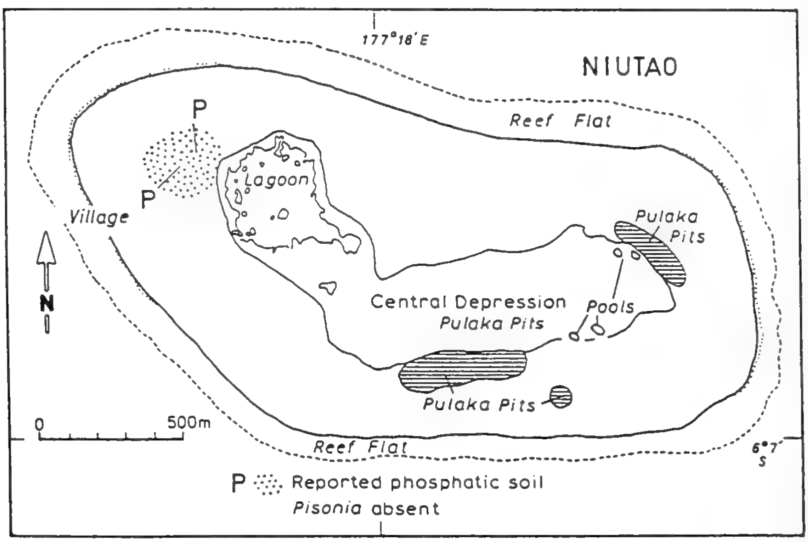


FIG. 2. Locality map Niutao. After McLean, Holthus, Hosking, Woodroffe and Hawke (1986a).

Holthus, Hosking and Woodroffe (1986a) mapped some 20 ha of phosphate soils covering 5.5% of the atoll's land surface.

On Nanumea islet, several blocky outcrops of phosphatic calcirudite and associated soils, which extend to 20-30 cm depth, occur beneath *Thespesia* woodland surrounding Te Milo pond. Phosphate in this area is restricted to the margins of this basin and outcrops atop abrupt slopes bounding the pond.

Two areas of phosphatic soils occur on Lakena. Both extend west of the *pulaka* (taro) pit area across the inner slopes of a coastal ridge and the edges of a central depression. They are separated by a zone of dark, sandy soil containing patches of sparse phosphatization. Soil profiles in both areas show an abrupt boundary between top soil and parent sediment at a depth of 25-30 cm (McLean *et al.*,, 1986a). Towards Te Tongo, the surface is littered with blocks of consolidated phosphatic limestone mixed with calcareous gravel. Close to Te Tongo are sandy phosphatic soils, presumably those noted by White. Only on Lakena is *Pisonia grandis* found growing on phosphatic soils; three trees in all.

NIUTAO

Niutao is a small, 2.5 x 1.15 km reef island occupying nearly 80% of the available reef top, with its coast paralleling the unbroken, roughly oval, reef edge and its long axis oriented westnorthwest-eastsoutheast (Fig. 2). The island is saucer-shaped with a central depression occupying some 57 ha and containing a small lagoon and swamps in the west and a gravel covered hardpan in the east. This depression was probably a lagoon, now isolated from the sea by the surrounding sand and gravel ridges. Total land area is about 235 ha.

The island is notable in lacking any *Pisonia* or any other substantial broadleaf woodland as well as any mature *Pisonia* trees (McLean, Holthus, Hosking, Woodroffe and Hawke, 1986a). White (in White and Warin, 1964) found no phosphate. On the basis of information provided by residents, McLean *et al.,* (1986a) mapped but did not visit an area of phosphatic soils northeast of the village where small specimens of *Pisonia* were also believed to be sprouting. Searches by Dr Urslua Kaly in 1990 failed to find any phosphatic limestone outcrops in this area or elsewhere on the island (*pers. com.,* September 1990).

NANUMAGA

Nanumaga is a roughly oval, 3 x 1.5 km, reef island surrounded by an unbroken fringing reef and occupying some 77% of the available reef top (Fig. 3). The island's surface is saucer-shaped with a broad central depression occupied partly by small lagoons and ponds which, along with their swamp margins, cover some 57 ha. Maximum elevation is about 8 m on the western lee edge. Total land area is some 282 ha.

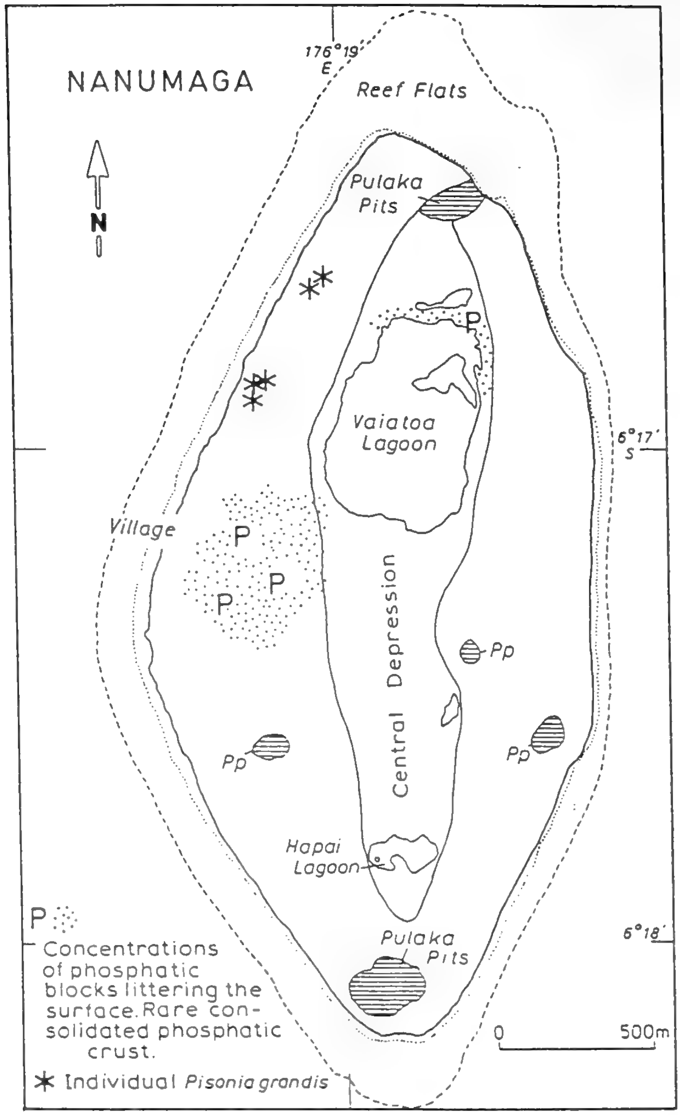


FIG. 3. Locality map Nanumaga. After McLean, Holthus, Hosking and Woodroffe (1985).

White (in White and Warin, 1964) reported no traces of phosphatization either on the surface or in several auger holes drilled to 2-2.5 m but McLean, Holthus, Hosking and Woodroffe (1985) mapped two areas of phosphatic soils covering about 13 ha. The largest extends eastward from the village to the mangrove fringe of Vaiatoa Lagoon. The second skirts this lagoon's northern shore. Both demarcate major concentrations of loose phosphatic limestone blocks which litter the surface and extend to a depth of 15-30 cm in a matrix of dark, phosphate-coated, ill-consolidated, calcareous sands and gravels. Coherent crusts of phosphatic limestone are exposed only rarely on the surface.

Pisonia woodland is absent from Nanumaga, the only *Pisonia* present being a few isolated individuals in the northwest. *Thespesia* is also generally absent.

VAITUPU

Vaitupu is an elongate, roughly pear-shaped island about 5.6 x 3.2 km, with its long axis lying northwest-southeast, and surrounded by a broad fringing reef (Fig. 4). There are two, small, shallow lagoons, Te Loto in the north and Te Namo in the south. Both are bordered by wide flats of fine calcareous mud.

Two large areas of phosphatic rocks and soils have been recognized on Vaitupu by both White (in White and Warin, 1964) and McLean, (pers. com. 1987). The first occurs near the center of the island about midway between the two lagoons. It consists of a phosphatic biocalcarenite crust ranging from a few centimeters to half a meter thick and covering an area of 8.17 ha. Variable-sized, mottled blocks of phosphatic biocalcarenite are scattered through a rich dark loamy crumb-structured soil. In places, similar blocks extend to a depth of more than half a meter in clean calcareous sand. *Pisonia/Hernandia* broadleaf woodland covers much of the area which also includes part of the Agricultural Department experimental station. White estimated a total of 25,000 tons of phosphatic rock were present, averaging 20% P_2O_5, although his figures appear to be based on a smaller areal extent of outcrop (~6 ha) than mapped by McLean.

Patchy phosphatization affects an area of about 5.5 ha on the eastern shores of Te Namo where it extends to a depth of 50 cm. White described the affected calcareous sediment as finer grained and more compact than at the other deposit and containing much broken shell and fine coral. McLean (pers. com. 1987) however, found an abundance of coral gravel and mapped the area as "phosphatic gravelly sands", in contrast to the northern sandy phosphatic soils. Tonnage was estimated by White as half that of the northern deposit.

White considered Vaitupu as the most productive of the Ellice Islands. In large part he believed this reflected the presence of an extensive, albeit thin covering of phosphate. However, it should be noted that by the early sixties when White visited, Vaitupu had become a show piece of the Ellice Islands due mainly to an intensive program of work

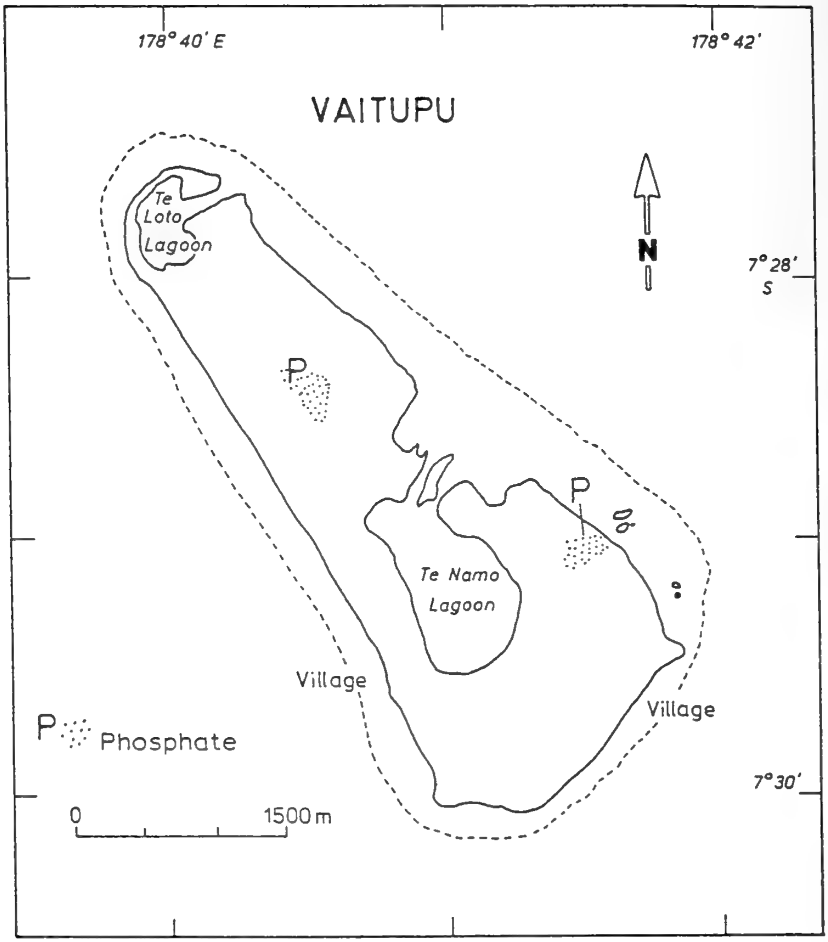


FIG. 4. Locality map Vaitupu.

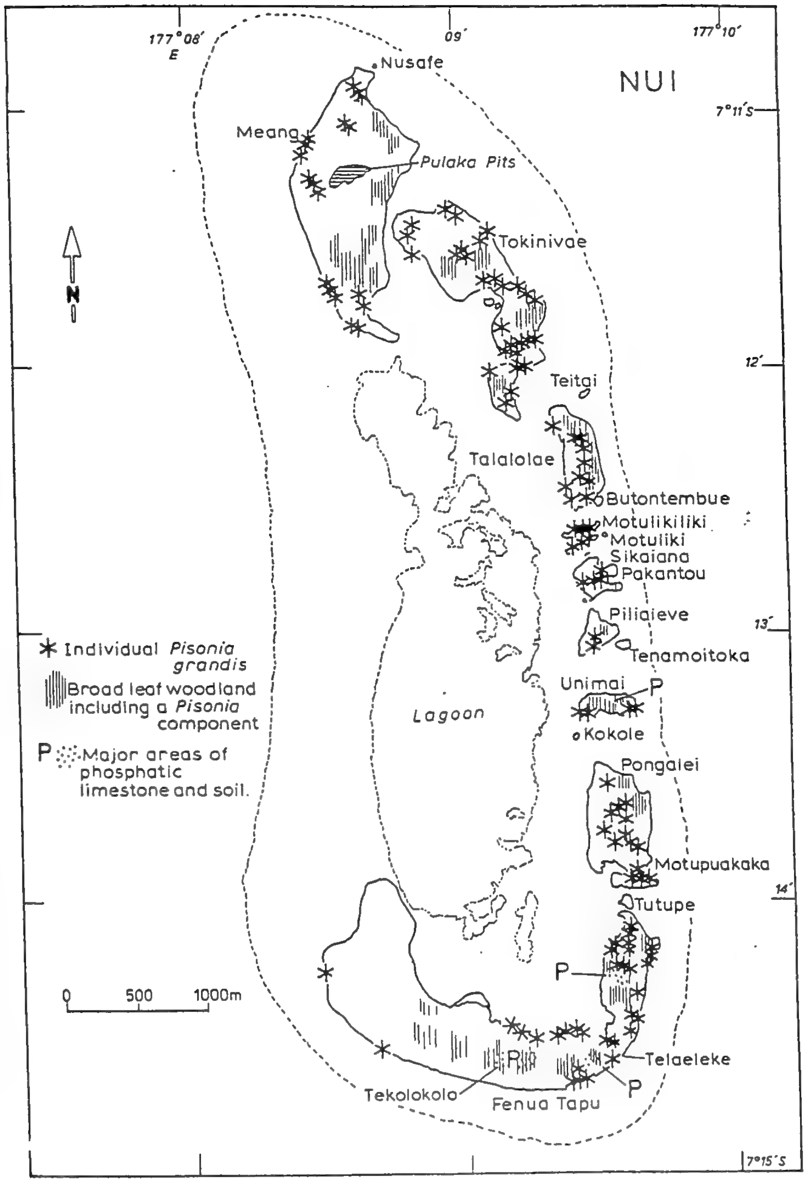


FIG. 5. Locality map Nui. After McLean, Holthus, Hosking, Woodroffe and Hawke (1986b).

instituted to repair the ravages of World War II (Lifuka, 1978, pp.102-3, footnotes 6,7). The result was in sharp contrast to the still damaged appearance and agriculture of the other islands (e.g. Luomala, 1951; Tudor, 1966).

NUI

Nui is an elongated, crescentic atoll about 7.25 x 2.5 km with its long axis oriented north-south (Fig. 5). Land area is 351 ha comprising 18 separate islets spread in a chain around the atoll's northern, eastern and southern sides. Fenua Tapu in the south accounts for 40% of this land area with Meang in the north contributing a further 25%. The western side of the atoll consists of a bare reef flat, 600-1000 m wide, and exposed at low tide. The lagoon is comparatively small and lacks any direct passage to the sea.

McLean, Holthus, Hosking, Woodroffe and Hawke (1986b) observed that the most mature soils of Nui - including the phosphatized horizons - occur in the central flat and surrounding ridge areas of the larger islets. These authors mapped three areas of phosphatized soil on Fenua Tapu, the largest being at Te Kolokolo. The parent rock is a coarse, calcareous, semi-consolidated calcirudite containing sandy lenses and forming part of the older ridges of the interior of this islet. Broken blocks of consolidated, botryoidal, phosphatic limestone are scattered across the ground surface and extend to a depth of 20-30 cm with occasional blocks being found to 60 cm. McLean *et al.*, reported that the parent material below is substantially unmodified, but White (in White and Warin, 1964) had described this deposit as differing from those examined elsewhere in Tuvalu in having its base "everywhere gradational into the underlying sands" (p.89) and he interpreted this as a consequence of the thick cover of "salt brush" keeping the phosphatized zone in a permanently moist state and promoting the downward leaching of the phosphate. Twenty years later, Woodroffe (1985) described the cover as being dominated by tall *Pisonia*, many reaching 20m, with *Ficus, Morinda* and *Acalypha* being important and the ferns *Nephrolepis, Polypodium* and *Asplenium* occurring as groundcover. *Pisonia* trees have been extensively felled in this area but regrowth is occurring from fallen limbs. White gave the dimensions of the Te Kolokolo deposit as approximately 90 x 75 m with an average thickness of 25 cm. He estimated 3000 tons were available containing 10-15% P_2O_5.

Two further, smaller deposits occur on Fenua Tapu. The substrate of both is calcarenite. That at Telaeleke occurs beneath an impressive stand of *Pisonia* woodland.

Incipient development of phosphate in areas of dark soils was noted on Fenua Tapu by McLean *et al.*, (1986b) as well as on the islets of Meang and Unimai. In total, these workers mapped 3.07 ha of phosphatic soils on Nui, representing 0.87% of the land surface.

NUKUFETAU

Nukufetau is a rectangular atoll, 14 x 8.25 km, with its long axis oriented northeast-southwest. 85% of the reef platform consists of bare reef flat (Fig. 6). Total land area of 331 ha comprises 37 separate islets with a narrow, almost continuous strip of land forming the southeastern side of the atoll. Two reef passes, Te Ava Amua and Te Ava Lasi, connect the lagoon to the open sea.

White (in White and Warin, 1964) reported phosphatized sand covering much of the surface of Sakalua (Coal Island), a small sand bank near the lagoon entrance. This deposit was subsequently mapped by McLean, Holthus, Hosking and Woodroffe (1986b) and investigated briefly by Radke (1985,1986). The islet measures 300 x 150 m and reaches no more than 1.5 m above sea level. 3.45 ha of the surface is covered by a crust of phosphatized calcarenites and calcirudites which averages 15-20 cm thick but commonly extends up to 30 cm deep. While the crust is fairly uniform in appearance, it is somewhat patchily developed beneath *Thespesia* scrub. White (p.92) interpreted the uneven development as "indicating that the original guano deposition was not uniform over the entire island". A central depression on the islet is floored by muddy phosphatic soil which renders it sufficiently impermeable to hold water after rain. At the margins the crust passes into calcareous beach rock and in an eroded section through the crust on the south-eastern shore of the islet, Radke (1986) described solution depressions in the underlying limestone as rimmed and partially infilled by dark phosphate. Phosphate levels were highest in the top of the section (61% $Ca_3(PO_4)_2$), passing to 49-41% below.

Radke (1985, 1986) reported phosphatized limestone from Savave, from the reef flat east of Teafoune, from the reef flat to the north of Motumoa, central Motumoa, and believed it to occur also on Lafaga. McLean *et al.,* (1986b) also mapped an area of 2.9 ha on the western side of Motulalo where phosphatic soils are patchily developed within an area of otherwise dark soil covered by *Hernandia* woodland.

Following his 1985 survey, Radke considered that Nukufetau was one of the more likely of Tuvalu's islands to have submarine phosphate deposits within the lagoon, the floor of which extends to a maximum depth of 30 m. Subsequently, he conducted a seismic survey and located two major reflectors, both of which he interpreted as unconformities within the lagoon sediments (Radke, 1986). The shallowest of these occurs 4-12 m below the lagoon floor and is possibly associated with surface lag deposits contained in erosional channels. The second lies 10-40 m lower is related to two large bodies, presumably of sediments, occurring lagoonward of Te Ava Lasi and Faiava Lasi-Lafaga-Niuatui. No subsequent work has been undertaken to ascertain if phosphatic lag-gravels form part of these deposits.

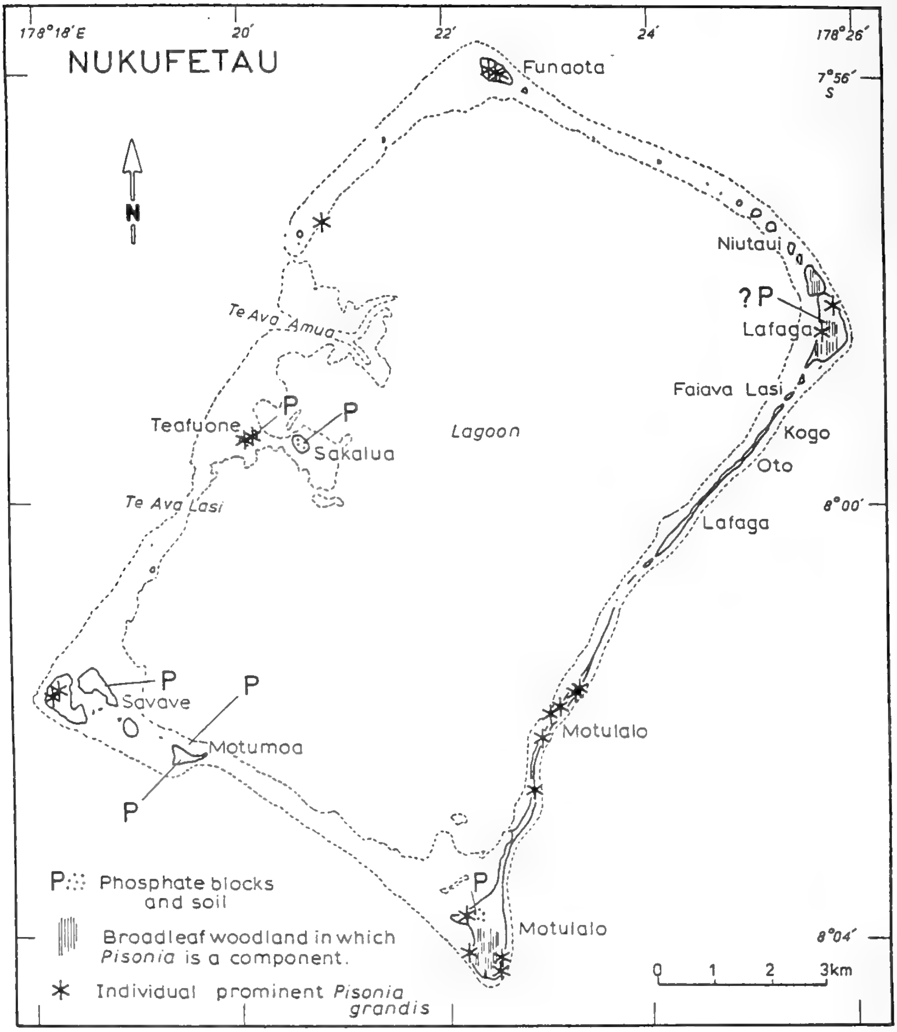


FIG. 6. Locality map Nukufetau. After McLean, Holthus, Hosking and Woodroffe (1986b).

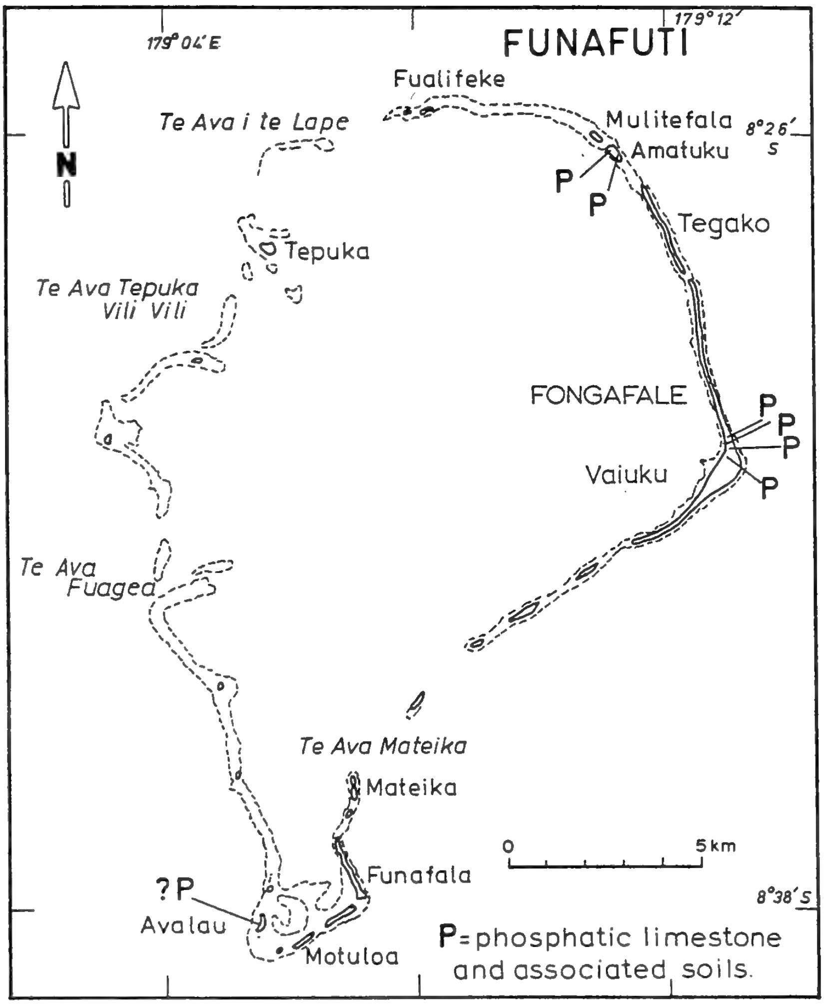


FIG. 7. Locality map Funafuti.

FUNAFUTI

Funafuti is the largest atoll of the group, being roughly pear-shaped, with its narrow-end directed south (Fig. 7). The lagoon is 16 x 13 km and approximately 45 m deep. It is surrounded by some thirty islets, a number of which form an almost continuous line on the eastern (windward) side; the longest being Fongafale which extends over 11 km.

Phosphatic rocks and a soil sample from Funafuti were collected during the first Royal Society coral reef boring expedition of 1896 and reported on by Cooksey (1896), David and Sweet (1904), Judd (1904) and Sollas (1904). These appear to have come from three localities. No similar soils or rocks were described from collections made during the 1897 and 1898 expeditions.

Judd (1904, p.372) described a dark brown rock "obtained by Professor SOLLAS from behind the Mangrove Swamp near Fongafale in the main island of the atoll". Two analyses yielded 21.74 and 29.07% "calcium phosphate". It may be noted. that geographic usage in the Royal Society's report differs from that of the present day. "Funafuti" was used in the report for both the atoll itself as well as the main islet of that atoll. "Fongafale" was regarded as the main center of that islet. Present usage has Fongafale as the main islet of the atoll of Funafuti.

The locality of Judd's samples was close to a "taro plantation" from which Hedley had collected a soil, an air dried sample of which Cooksey (1896, p.76) had found to contain 6.00% P_2O_5 and had concluded "would seem to shew that a considerable quantity of animal matter, either in the shape of bones or excrement has been added to this soil as manure". David and Sweet (1904, p.68) commented that this soil had perhaps had a certain amount of "guano" added to it but it "should be mentioned that the soil...has been enriched in places by material carried there by natives from other islets in this atoll, and we were informed that a little of the soil had been bought over as ballast from Samoa."

The taro plantation referred to was presumably the main *pulaka* (taro) pit on Fongafale dug to the local water table. The ground around this and similar dug pits elsewhere in Tuvalu is littered with spoil. The soil within is little more than a poorly drained calcareous ooze with a high organic content due to its being regularly mulched with vegetable refuse. Phosphatic rock and soil has been added to such pits in an attempt to improve productivity for at least a hundred years, on an unsystematic and irregular basis. Hedley may have fortuitously sampled a soil that had been artificially enriched but small outcrops of phosphate rock occur in several places on Fongafale and trenches, opened to a depth of 2 m for the laying of power reticulation cables in the northern part of the main township, frequently encountered patchy phosphate deposits. Field investigations by the author in 1984, 1986 and 1988 indicate that a thin but extensive subsurface crust of phosphate exists in this area of Fongafale near the site of the 1897-98

Royal Society bore hole. Perhaps it was this deposit which was exposed in and alongside the pulaka pit in 1896 as well as "behind the mangrove swamp."

Judd (1904) reported on two other specimens of brown phosphatic rock collected by Sollas from "the islet of Avalau, lying north of the main island of Funafuti" (p.372). Again there is geographic uncertainty. Avalau is an islet at the extreme south of Funafuti. Sollas (1904), however, described phosphate-rich rock from Amatuku islet, in the north of Funafuti. Possibly this was where Judd's specimens came from. The two yielded 14.40 and 26.34% "calcium phosphate"; the brown matrix containing 32.5% and the white limestone fragments within the matrix 5.79%.

The Amatuku deposits outcrop just short of the western tip of that islet. Rodgers (1989b) described the greatest thickness as occurring on the lagoon beach where phosphatic limestone extends from beneath the low tide zone to the top of the islet's 1.5 m terrace on which a jumble of broken phosphatic blocks extends across the 20 m width of the island. On the ocean coast the phosphatized horizon is less than half a meter thick and confined to the supratidal terrace. Sollas (1904) described the beds on the lagoon coast as forming a low cliff rising "5 feet above high-water springs. In places they are undercut and fallen fragments lie on the lagoon platform. The dip of the beds is a few degrees (3° to 4°) to the W.N.W." (pp.24-5). The cliff is now eroded and phosphatic limestone occurs as small phosbergs (Stoddard and Scoffin, 1983) within a gravel strewn beach. The rocks alternate between biocalcarenites and biocalcirudites in which the clast size is variable but commonly between 8 and 30 mm dia. Sollas regarded the beds as water-laid and noted that the smaller bioclasts were typically "chalk-like", a feature which later workers in similar rocks have repeatedly drawn attention to. Sollas cited Judd as having found up to 25% calcium phosphate in one sample while Flynn and Makin (1976, p.29) quote McLean (pers.com.) as finding the Amatuku deposit to contain "about 80% mineral phosphate". Quite what is meant is obscure. The phosphate of the rock is no more than a thin coating around the calcareous bioclasts. Small, low, dark brown outcrops of phosphatic limestone occur as inland exposures at Fongafale as well as around buildings in central Amatuku.

In passing, it may be noted that Judd (1904, p.372) reported that no phosphatized rock had been encountered in any of the Royal Society borings on Funafuti and that the recovered dolomitic and calcitic cores contained "only very minute quantities" of phosphate; eight samples from 15 to 1108ft depth showing a range of 0.12-0.29% calcium phosphate and Cullis (1904, p.392) observed that this small amount was probably present "as an invisible impurity; it has not been detected as a distinct mineral".

NUKULAELAE

Nukulaelae is an elongate atoll with a narrow 3.3 km waist, an 11 km long axis oriented northwest-southeast, and rounded ends (Fig. 8). The reef forms an unbroken

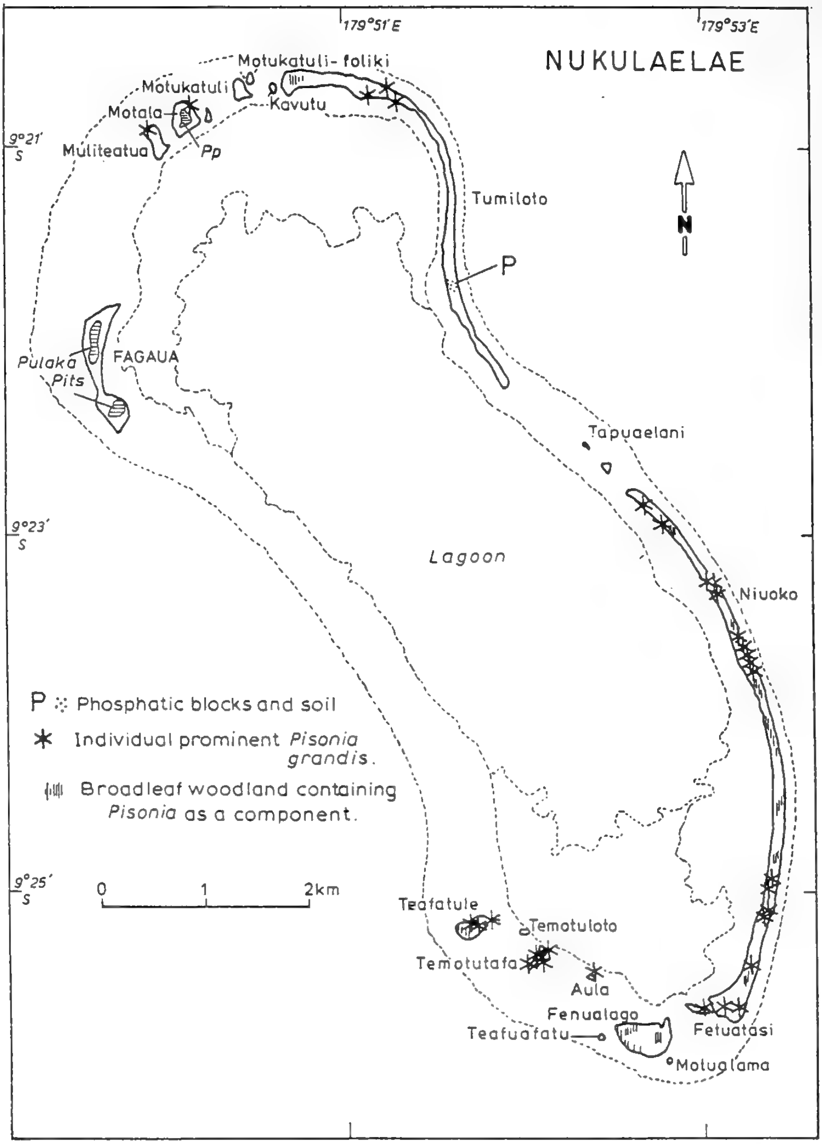


FIG. 8. Locality map Nukulaelae. After McLean, Holthus, Hosking, Woodroffe and Hawke (1986c).

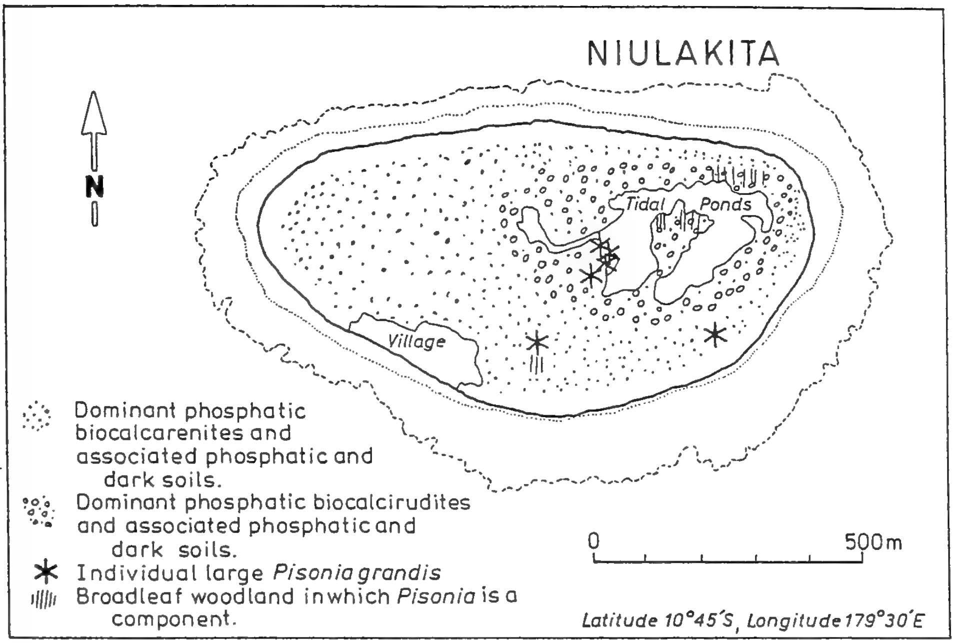


FIG. 9. Locality map Niulakita. After McLean and Hosking (1986).

perimeter about the lagoon. On the eastern, windward side, two narrow, 150 m wide islets form an almost continuous strip of land. Several small islets occupy the northern and southern ends, while only one islet, Fangaua, occurs on the leeward reef. Total land area is about 183 ha.

White (in White and Warin, 1964) failed to locate any trace of phosphate on either Fangaua or Tumiloto (Motuloa) but McLean, Holthus, Hosking, Woodroffe and Hawke (1986c) found a small area of phosphatic blocks and soil in south central Tumiloto in a coconut replant area which they considered had once been covered by *Pisonia* woodland. This islet consists of two, low, parallel, sandy rubble ridges flanking both the lagoon and ocean shores, and separated by a somewhat swampy, trough-like depression, up to 90 m wide. The deposit is part of the lagoonside terrace which rises 1.5 m above the adjacent beach. Blocks of phosphatized calcarenite, commonly 5-30 cm across, are littered over the surface in a matrix of loose sandy soil, smaller phosphatized clasts and roots and extend to a depth of 12 cm. Below this level the sand is stained with phosphate for only a short distance. Surface blocks can be found scattered for over a 100 m across the islet continuing into the central depression but becoming less common towards the ocean. Total area over which they occur is about 0.9 ha.

It was of Nukulaelae that Graeffe (1876, p.1161) made specific reference to "die Excremente der Seevögel, die sich gern auf solchen kleinen Banken aushalten, ebenfalls humus bildend".

NIULAKITA

Niulakita is a small, roughly oval (900 x 500 m) reef island, broadening slightly to the south, and with its long axis oriented east-west (Fig. 9). The land area of 40 ha occupies about two thirds of the possible reef top. The narrowness of the surrounding reef and the exposure of the coast to wave action, results in the island's beaches reaching higher levels than those of other islands of the archipelago, while the usual distinction between windward and leeward side is less apparent (McLean and Hosking, 1986).

Niulakita is the most southerly island of Tuvalu. It enjoys the highest rainfall of the group and has long been renowned for the relative richness of its soil and the range of crops which can be grown. Phosphatic soils dominate on this island, covering 70% of the land area. Along with the associated phosphatized limestone crust, they were exploited in the late nineteenth century and small quantities shipped to Auckland, New Zealand, between 1889 and 1902 (Nia, 1983). No records of this activity are known and the extent to which soil profiles and land surface were disturbed is difficult to assess. Subsequent reports on the extent of the remaining phosphate are conflicting (Archives of High Commissioner of the Western Pacific e.g. Schulze, 1903; British Phosphate Commission unpublished reports; White and Warin, 1964; Flynn and Makin, 1976; Nia, 1983; McLean and Hosking, 1986). While the deposit may be insignificant when compared with those

at Nauru and Ocean Island, the surveys of Flynn and Makin (1976) and Mclean and Hosking (1986) indicate that the rocks and associated soils are still the most extensive, sub-aerial phosphate deposit in Tuvalu, exceeding 500,000 tons but of unknown grade.

A beach berm ridge swale complex surrounds the island. The central eastern half of the island consists of a depressed area which contains a number of irregular ponds which fill and drain in response to tidal movement. Their margins are steep scarps, 1-2 m high, developed in strongly phosphatized biocalcirudite. The western and southern half of the island is a more or less featureless flat, bordered by the coastal ridge.

McLean and Hosking (1986) distinguish two main variants of phosphatic and dark soils: those which are predominantly sandy and those dominated by gravel. Within each textural variety they were unable to map separate areas of phosphatic and dark soils. Compared with soils developed elsewhere in Tuvalu, including the remainder of Niulakita, these soils are darker in color, have a deeper top soil and show a more distinct break between soil and parent material. Top soils have a high (~30%) organic content and are invariably non-calcareous and even mildly acidic. Those formed above calcarenite substrate possess a crumb and nut structure seen elsewhere in Tuvalu only on Vaitupu where it is not as extensively developed.

Sandy phosphatic soils are typically 40-50 cm thick and commonly have a surface cover of fresh or partly decomposed organic matter mixed with 2-5 cm diameter phosphatic limestone blocks. Beneath, the profile comprises 2-5 cm dark brown loamy top soil over a reddish brown loamy sand speckled with white bioclastic sand grains and containing partially consolidated 2-5 cm diameter blocks. Frequently a hardpan of indurated phosphatic limestone up to 20 cm thick occurs a few centimeters beneath the surface and is also exposed over considerable areas of the island where the top soil has been removed. Whether this second horizon has been indurated or not, there is an abrupt break to a lower 15-20 cm zone of lighter, brownish grey, stained sand. The intensity of the staining declines with depth until unaltered parent carbonate sands are reached.

Phosphatic gravelly soils are similar. Apart from textural differences, the horizon differentiation is poorer and the hardpan thicker, often reaching up to 2 m about the eastern ponds. Irrespective of type of vegetation cover, the ground surface is littered with a dense cover of fresh and decomposing organic matter mixed with algal coated rubble and phosphatized carbonate blocks. Top soil is a dark brown or reddish brown black gravelly loam, commonly 15-30 cm thick and showing both phosphatized and unmodified bioclasts set in a silty matrix. Beneath this topsoil, the gravel framework may be quite open with only dark staining around individual clasts, or voids can be infilled by either stained sand or organic mud. In places where the latter is present, the entire subsurface layer is firmly cemented together and only broken into blocks by penetration of tree roots.

TABLE 2. Summary of Areal Extent of Crustose Phosphates in Tuvalu and Relationship with *Pisonia* grandis

Island Islet	Area of phosphate and related soils, ha*	% total land area*	Area of *Pisonia* and related broadleaf ha*	Remarks
Nanumea	20.06	5.48	0.10	No *Pisonia* growing on phosphate
Lakena	18.27	15.35	nil	
Nanumea	1.79	0.80	0.10	
Niutao	3.72	1.58	nil	*Pisonia* saplings growing on phosphate
Nanumaga	13.19	4.39	nil	*Pisonia* and *Thepesia* generally absent
Nui	3.07	0.87	4.97 (pure *Pisonia*) 5.45 (*Pisonia* + *Hernandia*) 20.80 (*Pisonia* + coconut)	
Vaitupu	13.66	2.58		
Nukufetau	6.45	1.95	14.84	*Pisonia* growing on phosphate
Motulala	2.90	3.05	4.85	
Sakalua	3.45	56.18	nil	
Funafuti	0.01	0.01	not known	No *Pisonia* growing on phosphate
Nukulaelae	0.90	0.49	0.74	No *Pisonia* growing on phosphate
Nuilakita	29.31	69.68	0.27	Scattered *Pisonia* abound throughout island. Saplings on phosphate common. *Hernandia* common associate.

* Data largely from McLean *et al.*, (various dates), that from Niutao being suspect - see text.

It should be noted that McLean and Hosking (1986) found that *Pisonia* woodland *per se*, covers only 0.27 ha or 0.63% of the island. However, medium sized *Pisonia* are dotted throughout the coconut woodland of all the central (phosphatized) area and small saplings of *Pisonia* are widespread in the understory vegetation. The main areas of *Pisonia* woodland occur around the central pools, east of the village. *Hernandia* may be mixed into the canopy. The ground is either bare or covered with *Asplenium* and *Phymatodes*.

GEOBOTANY

A strong geobotanical relationship is alleged to exist between low island phosphates and *Pisonia grandis* (e.g. Shaw, 1952; Fosberg, 1957).

Common elements in the apparent association of *Pisonia,* certain bird species and the occurrence of low island phosphates are:

(i) a strong preference for some birds to use the trees as roosts and nesting sites (e.g. Merrill in Christopherson, 1927).
(ii) dispersal of the glutinous seeds by birds when these become embedded in feathers (e.g. St John, 1951).
(iii) accumulation of raw humus beneath *Pisonia* groves - an unusual occurrence on tropical low islands (e.g. Fosberg, 1957).
(iv) development of black-brown, organic-rich soil containing abundant calcium and water soluble phosphate and low carbonate, with a pH 5.0-6.5 (e.g. Mayor, 1924; Lipman and Taylor, 1924; Christopherson, 1927).
(v) a phosphatized hard pan beneath the soil, commonly 10-20 cm thick but up to 0.5 m with low or even nil carbonate - a true phosphatite (e.g. Christopherson, 1927).
(iv) a calcareous substrate.

Although a *Pisonia*-phosphate association may have existed in Tuvalu in the past, man-induced changes make it impossible to recognize such a relationship today throughout most of the archipelago, or indeed, to ascertain whether it was present in the virgin environment (Table 2). The species does not occur today at phosphate localities on five islands. On the remaining four islands, established *Pisonia* stands are found at four phosphate localities with saplings sprouting on parts of deposits. However, the tree grows luxuriantly where phosphates have not been identified, and new saplings have been observed sprouting on phosphate-free substrate (e.g., Nui). Only in some restricted areas of Niulakita are several of the elements enumerated above found associated. Consequently, the presence or absence of *Pisonia* in the present day should not be taken as a geobotanical indicator as, for example, is implied by Woodroffe (1981).

The same man-wrought changes in the Tuvaluan environment also make ineffectual attempts to appraise the relevance of models proposed by various workers, to explain *Pisonia*-phosphate relationships identified in other island groups.

For example, Shaw (1952) followed up observations of Christopherson (1927) in suggesting that *Pisonia grandis* required an abundant supply of phosphate, in association with limestone, at least for its germination and early development. He saw such edaphic conditions as being best provided in the zone immediately underlying bird colonies on reef islands where seeds carried by the birds could germinate. He further suggested that where the phosphate/guano supply becomes depleted, that *Pisonia* would gradually disappear.

Contrariwise, Fosberg (1957) suggested that *Pisonia* could provide the necessary ingredients for phosphatization of island rock. He drew attention to the humus build up and the acid nature of the underlying soil. These factors he interpreted as providing an environment to render soluble any phosphate in excreta of birds nesting in the trees. The resulting solution would be washed down through the humus by rain and the phosphates precipitated on reaching the alkaline limestone below, consequentially forming the typical hardpan. In such a model crustose phosphate would be an indicator of former *Pisonia* forests and an accompanying bird population.

Both models are plausible but difficult to appraise in the absence of critical data enabling cause and effect to be adjudged. Further, not only is a direct link between phosphate deposits and *Pisonia* lacking in Tuvalu today, but so is hard evidence for the involvement of birds (Rodgers, 1989a). The contribution of birds in supplying the phosphorous of the deposits is tacitly assumed by most writers yet, while they may well have been primary donors in Tuvalu's past, no present or former bird colony has been identified with any known phosphate deposit. No avian remains have been identified from any deposit. No phosphatization has been found occurring under any of the existing bird colonies in the group.

It may also be noted that when it is present on Tuvaluan phosphatic soils, *Pisonia* is but one element of a floral association which typically includes *Hernandia* and/or *Asplenium* as on Nui, Nanumea, Vaitupu, and Niulakita. *Polypodium, Ochrosia* and various elements of the *Barringtonia* formation, of which *Pisonia* is one component, are also commonly present.

DISCUSSION

Insufficient detailed field studies have been conducted for a complete picture of the relationship of the phosphate deposits within the geology of the islands of Tuvalu to have emerged but some general observations can be made.

Phosphatized limestones and associated soils occur on each of the nine islands of Tuvalu. They are a normal aspect of low island geology and are products of a process which has phosphatized calcareous substrate, cutting across pre-existing sedimentary, pedological and biological structures. The seemingly differing descriptions of the petrography of individual deposits represent no more than different sections of the varied, phosphatized atoll sediments seen by the different workers at the times of their differing visits, e.g. Te Namo (Vaitupu): White and Warin (1964) *vs* Mclean *et al.* (1987); Te Kolokolo(Nui): White and Warin (1964) *vs* Mclean *et al.* (1986b).

While size of the different deposits varies widely, phosphatization has been more extensive than surface exposures indicate. Excavations show subsurface deposits exist (e.g. Funafuti) whilst resurveys regularly turn up previously overlooked occurrences e.g. Nukufetau and Funafuti.

The precise relationship of cemented phosphate limestone, unconsolidated phosphatized sands and gravels, and phosphatic soil in Tuvalu is not fully understood and any distinction between phosphatic soil, sediment and rock may, to a great extent, be arbitrary as shown by the numerous soil profiles derived by McLean *et al.*, (various dates), representative examples being published in Rodgers (1989a). Rather than phosphatic soil being derived invariably by degradation of pre-existing phosphate rock, a consolidated horizon of phosphatic limestone rock, frequently occurs within the phosphatic soil profile with unconsolidated layers above and below. This consolidated hardpan may have formed by phosphatization of calcareous substrate, or of a pre-existing calcareous regosol or of an earlier formed unconsolidated phosphatic horizon. Frequently the hardpan is broken up and distributed throughout a later formed soil profile while indurated phosphate surface crust can be shown to be former soil hardpan, now exposed following erosion of an overlying unconsolidated horizon (e.g. at Niulakita: McLean and Hosking, 1986).

Surface outcrops are being physically eroded by the normal processes of mechanical weathering such as abrasion by wind and waves. Disruption of the deposits occurs through root wedging (e.g. Nui, Funafuti, Nukulaelae, Niulakita), and the activities of man (e.g. Funafuti, Vaitupu) and domesticated animals, particularly pigs (e.g. Amatuku). Wave and wind activity during tropical storms has heavily modified some coastal outcrops in historic times (e.g. Nukufetau, Funafuti).

Where phosphate rock/hardpan is exposed, it controls the local geomorphology insofar as it is more resistant to weathering than unphosphatized calcareous substrate. Phosphatized rocks form low lagoonal cliffs (e.g. Amatuku: Sollas, 1904), phosbergs in the intertidal zone (e.g. Amatuku: Rodgers 1989b), extensive surface crusts (e.g. Sakalua: White and Warin, 1964), or resistant boulders protruding from surfaces (e.g. Fongafale).

Chemical weathering is slight, with hydroxyapatite having a reduced solubility under the high pH conditions of natural atoll waters. Induration of inland outcrops is occurring in a manner similar to that described in the weathering of typical calcareous phosphorites (Altschuler, Clarke and Young, 1958). Differential dissolution of carbonate yields a resistant, fine-grained phosphate residue which gets swept into previously unfilled pores (cf. Niulakita).

No evidence has been found of present day phosphatization in Tuvalu, possibly because it has not been looked for, but much subsurface hardpan phosphate appears extremely fresh, lacking the powdery, degraded, residual appearance of surface outcrops. Evidence elucidated by Radke (1986) from Sakula (Nukufetau) indicates that the phosphatization process has been either continuously or at least episodically active throughout the last 4000 years i.e. for at least as long as the islands have existed more or less as they are today.

Conventional wisdom regards low island phosphatic crust as formed within the vadose zone (Stoddard and Scoffin, 1983) with the relatively sharp junction at the base of most hardpans indicating an abrupt planar limit on the deposition of phosphate. The width and depth of hardpan at Tuvalu perhaps reflects fluctuation of the vadose environment within the substrate. The height of the vadose zone varies with the coarseness of the substrate sediment and it can be noted that the thickness of the hardpan often varies with coarseness of the cemented clasts (e.g. Niulakita.)

The mineralogy of the deposits, the source of the phosphate, and the mechanism whereby it accumulates in the vadose zone are discussed elsewhere (e.g. Rodgers, 1989a,b). Suffice to say here that present deposits are regarded as exhumed accumulations of carbonate hydroxyapatite, formed in vadose zones related to former higher sea levels. Phosphorous is believed to have been surface derived from both terrestrial and marine organisms including, birds, plants, and degradation of the biominerals of the calcareous substrate. Transport from the surface to the vadose zone, through the high pH soils of the islands, was probably via humic complexes (cf. Fosberg, 1957). If humic phosphate continues to arrive in or at the water table, and with discharge of soluble phosphorous to the sea being limited (e.g. Elpatievsky, 1985), any soluble phosphate must be either recycled out or removed from solution if eutrophication of the atoll's fresh water lens is not to occur (cf. Brown, 1973). Precipitation of phosphorous as insoluble apatite in the vadose zone would effectively remove the element from further immediate participation in the atoll's biogeochemical cycle, and thereby prevent eutrophication of the atoll water tables as progressive amounts of phosphorous are cycled through them.

ACKNOWLEDGMENTS

The major unpublished sources that were consulted are held in the offices of CCOP/SOPAC, United Nations Development Program, Suva, The National Library and Archives of Tuvalu, and the Department of Geography, University of Auckland, New Zealand. Thanks are owed to Professor Roger McLean, Drs Peter Hosking and Colin Woodroffe, and to various staff of CCOP/SOPAC who freely provided documents, maps and information, and gave permission to use their information. The late Sam Rawlins of Funafuti, Tuvalu, introduced the author to the phosphates of Amatuku as well as obtaining and supplying samples. Fred Pullen and Teu Manuella from Ministry of Commerce and Natural Resources, Tuvalu gave invaluable support. Professor Carrick Chambers of Royal Botanic Gardens, Sydney, made suggestions concerning the present status of our knowledge of *Pisonia grandis* with Dr Fosberg of the Smithsonian Institution providing advice on the same subject, not all of which was taken. Dr Alex Ritchie and Carol Cantrell of the Australian Museum furnished quarters conducive to study. Education and Leave, and Research Committees of the University of Auckland supplied funds enabling this work to be undertaken.

REFERENCES

Aharon, P. and Veeh, H.H., 1984. Isotope studies of insular phosphates explain atoll phosphatization. *Nature* **309**:614-617.

Altschuler, Z.C., 1973. The weathering of phosphate deposits - geochemical and environmental aspects. In: Griffith, E.J., Beeton, A., Spencer, J.M. and Mitchell, D.T., eds, *Environmental phosphorous handbook*. John Wiley, New York. pp.33-96.

Altschuler, Z.C., Clarke, R.S. and Young, E.J., 1958. Geochemistry of uranium in apatite and phosphorite. *U.S. Geological Survey Professional Paper* **314D**:45-90.

American Geological Institute, 1974, *Glossary of geology and related sciences*. 2nd ed. Washington. 325p.

Becke, L., 1906. *Notes from my south sea log*. Werner Laurie, London,

Brown, W.E., 1973 Solubilities of phosphates and other sparingly soluble compounds. In: Griffith, E.J., Beeton, A., Spencer, J.M. and Mitchell, D.T., eds, *Environmental phosphorous handbook*. John Wiley, New York. p.203-240.

Christopherson, E., 1927. The vegetation of the Pacific equatorial islands. *Bernice P. Bishop Museum Bulletin* **44**:1-79.

Cochet, A.M., 1900. Les îles Ellice. *Annales de Notre-Dame du Sacre-Couer,* July 1900:338-392.

Cook, P.J., 1975. Prospects for finding offshore phosphate deposits in the southwest Pacific (Project CCOP-1/REG-11). *United Nations Economic and Social Commission for Asia and the Pacific, Committee for Co-ordination of Joint Prospecting for Mineral Resources in the South Pacific Offshore Areas, Proceedings 3rd session CCOP/SOPAC, Apia,* 2-10 September 1974:75-85.

Cooksey, T., 1896. Rock specimens from Funafuti. *Australian Museum Memoir* **3**:73-78.

Cullen, D.J., 1986. Submarine phosphate sediments of the SW Pacific. In: Cronan, D.S., ed., *Sedimentation and mineral deposits in the southwestern Pacific Ocean.* Academic Press, London. pp.183-235.

Cullis, C.G., 1904. Mineralogical changes observed in cores of Funafuti borings. In: *The atoll of Funafuti: Borings into a coral reef and the results: Report, Coral Reef Boring Committee, Royal Society of London.* Harrison and Sons. Section XIV:392-420.

David, T.W.E. and Sweet, G., 1904. The geology of Funafuti. In: *The atoll of Funafuti: Borings into a coral reef and the results: Report, Coral Reef Boring Committee, Royal Society of London.* Harrison and Sons. Section V:61-124.

Duncan, R.A., 1985. Radiometric ages from volcanic rocks along the New Hebrides-Samoa lineament. In: Brocher, T.M., ed., *Investigations of the northern Melanesian borderland: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series* **3**:67-76

Elpatievsky, P.V., 1985. Soils of reefogenous islands as the phosphorous pool. *Proceedings, Fifth International Coral Reef Congress, Tahiti* **2**:119.

Flynn, G. and Makin, J., 1976. *A survey of the prospects for agricultural and industrial development in Tuvalu.* Mimeographed report. Scientific Units, United Kingdom Ministry of Overseas Development, London. 180p.

Fosberg, F.R., 1957. Description and occurrence of atoll phosphate rock in Micronesia. *American Journal of Science* **255**:584-592.

Gaskell, T.F., Hill, M.N. and Swallow, J.C., 1958. Seismic measurements made by HMS *Challenger* in the Atlantic, Pacific and Indian Oceans and in the Mediterranean Sea 1950-1953. *Philosophical Transactions of the Royal Society of London* **A251**:23-83.

Graeffe, E., 1867. Reisen nach verschiedenen Inseln der Südsee. *Das Ausland aus dem Gebiete der Natur-, Erd-, und Völkerkunde* **40**:1159-1164, 1184-1191.

Hedley, C., 1896. General account of the atoll of Funafuti. *Australian Museum Memoir* **3**:1-72.

Hutchinson, G.E., 1950. Surveys of existing knowledge of biogeochemistry 3: The biogeochemistry of vertebrate excretion. *Bulletin of the American Museum of Natural History* **96**:1-554.

Judd, J.W., 1904. Chemical examination of the materials from Funafuti. In: *The atoll of Funafuti: Borings into a coral reef and the results: Report, Coral Reef Boring Committee, Royal Society of London.* Harrison and Sons. Section X:167-185.

Lee, A.I.N., ed., 1980. *Fertilizer mineral occurrences in the Asia-Pacific region.* East-West Resource Systems Institute, Honolulu. 156p.

Lifuka, N., 1978. *Logs in the current of the sea.* Australian National University Press, Canberra. 110p.

Lipman, C.B. and Taylor, J.K., 1924. Bacteriological studies on Rose Islet soils: *Carnegie Institution, Marine Biology Papers* **19**:201-208.

Luomala, K., 1951. Logbook of a voyage to the middle of the earth. *Pacific Discovery* **4**:4-13.

McConnell, D., 1950. The petrography of rock phosphates. *Journal of Geology* **58**:16-23.

McLean, R.F. and Hosking, P.L., 1986. Niulakita. *Tuvalu Land Resource Survey Island Report*, Department of Geography, University of Auckland, **9**, 55p, A20p, 4 maps.

McLean, R.F., Holthus, P.F., Hosking, P.L. and Woodroffe, C.D., 1985. Nanumaga. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **2**, 72p, A40p, 4 maps.

______ 1986a. Nanumea. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **1**, 83p, A65p, 10 maps.

_______ 1986b. Nukufetau. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **6**, 81p, A28p, 20 maps.

McLean, R.F., Holthus, P.F., Hosking, P.L., Woodroffe, C.D. and Hawke, D.V., 1986a. Niutao. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **3**, 66p., A18p., 4 maps.

_______ 1986b. Nui. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **4**, 82p, A44p, 8 maps.

_______ 1986c. Nukulaelae. *Tuvalu Land Resource Survey Island Report,* Department of Geography, University of Auckland, **8**, 86p., A44p., 16 maps.

Mayor, A.G., 1924. Rose Atoll, American Samoa. *Carnegie Inst. Marine Biology Papers* **19**:73-91.

Morgan, W.J., 1972. Deep mantle convection plumes and plate motions. *American Association of Petroleum Geologists, Bulletin* **52**:203-213.

Nia, Nalu, 1983. Niutao. In: Laracy, H., ed., *Tuvalu, a history*. Institute of Pacific Studies, University of the South Pacific, Suva. p.58-65

Radke, B.M., 1985. Seismic and bathymetric profiling of Nukufetau lagoon, Tuvalu, for evaluation of phosphate potential, Tuvalu, February-March 1985. *Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC) Cruise Report* **108**, unpaged.

_______ 1986. Bathymetric and seismic features of Nukufetau lagoon, Tuvalu: An appraisal of submarine phosphate potential. *Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC) Technical Report* **57** (of PE/TU.9/Task 1), 28p.

Rodgers, K.A., 1987. The mineralogy of a phosphatic horizon, Amatuku islet, Funafuti atoll, Tuvalu. *South Pacific Journal of Natural Science* **9**:49-56.

Rodgers, K.A. 1989a Phosphatic limestones from Tuvalu (Ellice Islands). *Economic Geology* **84**:2252-2226.

Rodgers, K.A., 1989b. Dahllite and whitlockite from Amatuku, Tuvalu. *Mineralogical Magazine* **53**:123-125.

Rodgers, K.A. and Cantrell, C., 1987. Tuvalu's weather and climate: an annotated bibliography. *South Pacific Journal of Natural Science* **9**:111-142.

Sahng-Yup, Kim, 1981. Advisory report of the reconnaissance geology and mineral resources of Funafuti Atoll, Tuvalu. Unpublished. *RMRDC Report, Economic and Social Commission for Asia and the Pacific* no.130, 26p.

Schulze, O., 1903, Unpublished report. Archives, High Commissioner, Western Pacific, Funafuti.

Scolari, G. and Lille, R., 1973. Nomenclature et classification des roches sédimentaires (Roches detritiques terrigènes et roches carbonatées). *Bulletin, BRGM.*, **2**, section IV, no. 2:57-132.

Shaw, H.K., 1952. On the distribution of *Pisonia grandis* R. Br. (Nyctaginaceae), with special reference to Malaysia. *Kew Bulletin* no.1, 1952: 87-97.

Slansky, M., 1980. Géologie des phosphate sédimentaires. *Mémoire, BRGM.,* **114**:1-92.

Sollas, W.J., 1904. Narrative of the expedition in 1896. In: *The atoll of Funafuti: Borings into a coral reef and the results: Report, Coral Reef Boring Committee, Royal Society of London.* Harrison and Sons. Section I:1-28.

St John, H., 1951. The distribution of *Pisonia grandis* (Nyctaginaceae). *Webbia* **8**:225-228.

Stoddard, D.R. and Scoffin, T.P., 1983. Phosphate rock on coral reef islands. In: Goudie, A.S. and Pye. K., eds, *Chemical sediments and geomorphology*. Academic Press, London. p.369-400.

Tracey, J.I., 1980. Quaternary episodes of insular phosphatization in the central Pacific. In: Sheldon, R.P. and Burnett, W.C., eds, *Fertilizer mineral potential in Asia and the Pacific*. Proceedings, Fertilizer Raw Materials Resources Workshop, August 20-24 1979, Honolulu (East-West Resource Systems Institute, Honolulu), p.247-261.

Tudor, J., 1966. *Many a green isle*. Pacific Publications/Minerva, Auckland, 256p.

Warin, O.N., 1968. Deposits of phosphate rocks in Oceania. In: Proceedings, Seminar of Mineral Raw Materials for the Fertilizer Industry in Asia and the Far East: *ECAFE Mineral Resources Development Series* (United Nations, New York) **32**:125-132

Warner, J.B. and Rossfelder, A., 1978. Final report CEPAC-1, reconnaissance cruise, central Pacific. Unpublished report, Geomarex, 33p.

White, W.C. and Warin, O.N., 1964. A survey of phosphate deposits in the south-west Pacific and Australian waters. *Commonwealth of Australia Bureau of Mineral Resources, Geology and Geophysics, Bulletin* **69**:1-173.

Woodroffe, C.D., 1985. Vegetation and flora of Nui atoll, Tuvalu. *Atoll Research Bulletin* **283**:1-18.

ATOLL RESEARCH BULLETIN

NO. 361

BATIRI KEI BARAVI: THE ETHNOBOTANY OF PACIFIC ISLAND COASTAL PLANTS

BY

R. R. THAMAN

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

BATIRI KEI BARAVI: THE ETHNOBOTANY OF PACIFIC ISLAND COASTAL PLANTS[1]

R.R. Thaman[2]

INTRODUCTION

Jonathan Sauer (1961) remarked, in his Coastal Plant Geography of Mauritius, that the chance to study the coastal vegetation there was like being "admitted to a field worker's paradise" and stressed that "most tropical coasts are beautiful and exciting, particularly to people concerned with natural processes . . .." The same can certainly be said for the tropical coasts of the often Edenized islands of the Pacific Ocean. Their "beauty and excitement" is considerably enhanced, however, when one is also "concerned" with cultural processes and ethnobotany, in particular, the immense cultural utility of coastal plants, a factor which strongly influences the distribution and character of plant communities.

Because the use of plants, in particular, wild plants is so clouded in antiquity and so intimately associated with cultural origins, ethnobotanical research can shed considerable light on the the origin and nature of pre-European contact Pacific island societies. Ubiquitous coastal plant communities, because they are among the most useful, the most familiar to new settlers, and most subject to disturbance because of the attractiveness of coastal areas for human habitiation and development, would seem to be a particularly important focus for ethnobotanical studies.

There is, however, a relative paucity of Pacific-wide systematic ethnobotanical studies, with most prehistories, ethnographies and ethnologies of the area having focused on aspects such as settlement sequence and routes, carbon dating, blood groups and physical types (human genetics), material technology, linguistics, social organization, cosmogeny and major agricultural and food systems. Little emphasis has been placed on the use of and impact on indigenous plant resources and the wide array of supplementary crops and plants that sophisticated horticultural and maritime societies must have brought with them or used upon their arrival in the islands.

Although plant lists, floras, and vegetation studies, often including vernacular names and plant uses, exist for most of Polynesia, much of Micronesia and some of Melanesia (see references cited in Appendix), very few systematic ethnobotanical studies of Pacific island plants exist.

The paucity of ethnobotanical information may reflect both the rarity of plant remains, especially wild plant remains, in archeological deposits, as well as the extensive pre- and post-European-contact modification of coastal plant communities. An additional factor is the need for relative fluency in vernacular languages and/or knowledgeable and interested informants, if researchers are to successfully tap the wealth of ethnobotanical knowledge of traditional societies.

Notable exceptions, however, are Powell's (1976) comprehensive ethnobotany of New Guinea and ethnobotanical studies by Setchell (1924), Petard (1986), Whistler (1987), Whistler (1988), Krauss (no date), Luomala (1953), and Lessa (1977) of Samoa, Tahiti, the Cook Islands, Tokelau, Hawaii, Kiribati, and the Caroline Islands, respectively. Comprehensive studies such as

---

[1]. Batiri and Baravi are Fijian words for a mangrove coast and an open coast or beach, and the names of the author's daughter and son, respectively.

[2]. Geography Department, School of Social and Economic Development, The University of the South Pacific, Suva, Fiji.

Manuscript received 1 October 1991

Koch's material cultures of Tuvalu (1983) and Kiribati (1986); Hedley's (1896, 1897) ethnology and vegetation of Funafuti, Tuvalu; Te Rangi Hiroa (Peter Buck)'s Samoan Material Culture (1930) and ethnologies of Tongareva, Manahiki and Rakahanga atolls in the northern Cook Islands (1932a,b); Metraux's (1940) ethnology of Easter Island; Thompson's (1940) ethnography of Lau, Fiji; Oliver's (1974) study of Ancient Tahitian Society; and Manner and Mallon's (1989) plant list for Puluwat Atoll are also excellent sources. Neal's (1965) In Gardens of Hawaii also contains substantial information on plant use.

Also of particular ethnobotanical importance are Haddon and Hornell's (1975) comprehensive Canoes of Oceania, and studies of Pacific island food plants and subsistence agricultural systems by Massal and Barrau (1956), Barrau (1958, 1961), Handy et al. (1972), Jardin (1974), Catala (1957), Small (1972), Soucie (1983), and Thaman (1976, 1982ab), plus Yen's (1971, 1976, 1984) studies of the development of agriculture, with specific focus on arboriculture in Solomon Islands, and Merrill's (1943) study of emergency food plants and poisonous plants. Studies of the medicinal plants of Melanesia (Sterly, 1970), New Guinea/Papua New Guinea (Holdsworth and Mahana, 1983), Solomon Islands (Maenu'u, 1979), New Caledonia (Rageau, 1973), Fiji (Singh and Siwatibau, 1980; Waqavonovono, 1980; Weiner, 1984), Tonga (Weiner, 1971), Samoa (Mc Cuddin, 1974; Uhe, 1974), Hawaii (Kaaiakamanu and Akina (1922), Kiribati (Polunin, 1979), and Palau (Okabe, 1940) are valuabe resources, as are Brown's (1931) study of Polynesian leis and McDonald's (1978) comprehensive study of the leis of Hawaii. Together, these constitute a valuable body of knowledge of Pacific island plant resources and their uses, although, only in rare cases, focussing specifically on coastal plant resources and their utility.

This study, based on over twenty years personal observation and research on the use of Pacific plants, attempts to draw together, from such diverse sources, some of this knowledge. It examines the immense cultural utility of Pacific island coastal plants and the role that they have played in the successful habitation of the Pacific islands. It also attempts to provide a better understanding of the cultural sophistication and storehouse of empirical knowledge possessed by pre-European-contact societies. The geographical scope includes all those islands of Melanesia, Polynesia and Micronesia, extending from the islands of New Guinea and Palau in the west, to the Hawaii, French Polynesia, Pitcairn, and Easter Island in the east.

Finally, it is stressed that, because of the ecological and cultural importance of coastal plant communities, their impoverishment and the loss of ethnobotanical knowledge constitute an ecological, economic and cultural disaster. It is suggested that coastal reforestation and protection of coastal vegetation, coupled with a rejuvenation of traditional ethnobotanical knowledge, are among the most direct, cost-effective, self-help-oriented, and culturally-sensitive strategies for addressing both the short- and long-term obstacles to sustainable development in small-island states and coastal areas of the tropical Pacific Ocean.

The specific focus is on the ethnobotany of ubiquitous or locally important coastal strand, mangrove and coastal wetland plant species which are considered to be indigenous to, or long-established human introductions into, the Pacific islands. The Appendix lists some 140 coastal plant species or groups of similar species which are considered to be almost ubiquitous from, tropical Asia (the source region for many) to the smaller oceanic islands of the central Pacific, or which have particular localized ethnobotanical importance. All have the ability to cope successfully in environments characterized by loose shifting sands, soilless limestone and volcanic terraces and rock outcrops, high salinity, strong sunlight, strong winds and seasprays, and associated physiological drought (Fosberg, 1960), and, in some cases, periodic inundation and waterlogging.

These 140 plants include 10 ferns, 17 herbs, 11 grasses or sedges, 14 vines or lianas, 26 shrubs and 62 trees. All are commonly found in one or more of the following coastal vegetation categories: 1) the outpost strand or outer littoral zone closest to the high water zone characterized

by high soil salinity, salt spray and associated physiological drought; 2) the inner littoral zone; 3) mangrove habitats; and 4) coastal wetlands or marshes. Some of these are also found in a wild state or actively cultivated or protected in agricultural and fallow areas, secondary forests, and ruderal habitats or houseyard gardens in non-coastal environments (see Appendix).

Plants not included, but of considerable cultural utility, are those species restricted to only a few islands, and a number of indigenous species occasionally found in coastal forests, but usually restricted to more inland forests. Also beyond the scope of this paper are a wide range of recently introduced weedy exotics commonly found along Pacific coasts, particularly in disturbed or ruderal sites.

ETHNOBOTANICAL ORIGINS AND THE SETTLEMENT OF THE ISLANDS

According to some scholars, agriculture may have first evolved among sedentary fisherfolk in southeast Asia, the ancestral homeland of today's Pacific islanders in southeast Asia (Sauer, 1952; Anderson, 1967). In these rich coastal environments people, living primarily by fishing, would have been able to supply themselves with food without shifting from place to place. Archeological evidence, both from southeast Asia and the Pacific islands, indicates that these coastal societies had elaborate fishing gear consisting of boats, harpoons, and fish hooks, the latter indicating that there must have been fishing lines and probably nets using plants for cordage (Anderson, 1967). Sauer (1952) further stressed that, associated with this, would have been the development of plant-derived fish poisons, and other ethnobotanical developments such as netmaking, bark cloth manufacture, bark or thatch housing, folk medical technology, and the use and limited domestication of tuberous staples and tree crops, all of which would seem to tie into one ancient southeast Asian cultural complex.

In the Pacific islands, the coastal environment also seems to have been the focus of early settlement. There is evidence that the first settlement of the oceanic islands to the east of New Guinea by the Austronesian (Malayo-Polynesian) speaking Lapita Culture over three thousand years ago, was always coastal or on small offshore islands, and that these migrations and some later influences were all from island southeast Asia. The Lapita Culture (named after incised, applied-relief and paddle-impressed pottery characteristic of the group) constitutes a a number of highly mobile groups, which expanded very rapidly through Melanesia in the mid-late second Millennium B.C. and on into Polynesia, the present inhabitants of which are almost certainly their direct descendents. Other aspects of Lapita Culture also indicate that their economy was heavily oriented towards the ocean, marine fishing, long-distance oceanic voyaging, and inter-island transport of scarce materials such oven stones and obsidian (Bellwood, 1978).

THE UTILITY OF COASTAL PLANTS

Because of the perishability of plant remains, there is limited direct evidence of the widespread use of cultivated plants. However, based on linguistic and ethnobotanical evidence, as well as on the existence of vegetable scrapers, ovens and storage pits, it is probable that the Lapita peoples also had a wide range of domesticated or semi-domesticated plants (Bellwood, 1978). It must also be accepted, that they had in-depth knowledge of, and great use for a very wide range of wild plants, particularly ubiquitous coastal plants, which they encountered upon arrival at new islands. Handy et al. (1972) note that in Hawaii the area with which the Polynesian migrants first became familiar was the ko kaha kai (place [land] by the sea), which, although not favorable for agriculture, most of its varied plants found use in the "fishers" economy. In the atoll environment

of Kiribati, the diverse utility of almost all species is perhaps nowhere surpassed, with there being no word for weed (an unwanted or troublesome plant).

There are also indigenous or possibly indigenous coastal species, the distribution of which may have been assisted by the early inhabitants, because of their cultural utility. These include Cocos nucifera, Abrus precatorius, Barringtonia asiatica, Calophyllum inophyllum, Casuarina euisetifolia, Hibiscus tiliaceus, Inocarpus fagifer, Morinda citrifolia, Tephrosia purpurea, and Terminalia catappa (Merrill, 1954).

ETHNOBOTANY AND THE ALTERATION OF COASTAL VEGETATION

Ethnobotanical studies of coastal plants can be problematic due to the extreme alteration of coastal plant communities. As Sauer (1961, 1967) found on Mauritius and the Mexican Gulf Coast, much of the coastal vegetation had been severely altered by centuries of exploitation, including pre-European contact use of fire, clearing for agriculture in near-coastal areas, and the use of scarce timber resources for construction, and the production of a wide range of other objects.

Coastal areas, with their rich plant and fisheries resources, proximity to the sea (the main pre-road transportation route in most areas), and health-giving sea air (especially in areas plagued by malaria), were heavily affected and in some cases deforested by indigenous societies. Nypa groves were cleared to make way for taro gardens in coastal New Guinea (Barrau, 1958), and extensive pre-European contact coastal reclamation took place in the Langlanga Lagoon area of Malaita, Solomon Islands and on coastal islets in Pohnpei. Severe deforestation resulted from shifting cultivation and overpopulation on Lanai in Hawaii (Kirch, 1982) and Flenley and King (1984) go as far as suggesting that the megalithic Polynesian society of Easter Island (Rapa Nui) collapsed as a result of almost total deforestation. Handy et al. (1972) also discuss the pre-European contact elimination of wild plants in Hawaii from areas suitable for cultivation and, due to population increase, the use of trees for canoes, cooking tools, and handicrafts, and intensified foraging during times of drought.

Coastal forests have been widely replaced by coconut plantations, because coastal areas were most accessible to European influence and settlement (Barrau, 1958). In the Society Islands, the coastal zone, extending from the littoral to the bottom of the slopes and into the valleys, has been transformed more by human occupation than any other part of the islands (Oliver, 1974).

Species of particular value to Europeans for general construction, ship repair, and fuel for drying copra or beche-de-mer were undoubtedly first exhausted in the more accessible coastal zone. Sandalwood (Santalum neo-caledonicum) in New Caledonia's littoral forests became the object of intensive exploitation from the first arrival of Europeans. Catala (1957) cites the similar disappearance or decline in the numbers of important coastal species such as Barringtonia asiatica, Calophyllum inophyllum, and Cordia subcordata, in Kiribati, due to post-European-contact expansion of coconut plantations and their use for timber and fuelwood. There was also widespread destruction of coastal vegetation during World War II and resulting from open-cast phosphate mining in Nauru (Manner et al., 1984, 1985).

The destruction and reclamation of mangrove areas, often seen as unproductive marginal lands by Europeans, has been widespread. Considerable areas of mangroves have been reclaimed in Fiji, New Caledonia, and Solomon Islands for the expansion of sugarcane monoculture and urban development. Exploitation for firewood and charcoal production has been responsible for mangrove deforestation in Samoa, Tonga and Fiji and, in Truk, mangroves were completely removed by Japanese woodsmen (Fischer and Fischer, 1970).

In short, centuries of exploitation and reclamation of coastal strand and mangrove forests, coupled with monitization and modern in-the-school (away-from-plants) education and an associated loss of ethnobotanical knowledge and appreciation of the critical subsistence and developmental importance of coastal plants, have led to serious coastal deforestation and the endangerment and extinction of indigenous and traditionally important coastal species throughout the Pacific. The impoverishment of these plant communities represents a serious and continuing ecological, economic and cultural problem for coastal communities.

CULTURAL UTILITY OF PACIFIC COASTAL PLANTS

Table 1 shows the frequency of usage for specified purposes of the 140 plant species commonly found among Pacific island coastal and mangrove vegetation associations (Appendix). The analysis shows that there are some 75 different purpose/use categories for coastal plants, with the total frequency of usage for 140 plants being 1024, an average of 7.3 purpose/use categories per plant, ranging from no reported uses for only two species to as many as 125 for the coconut, if distinct uses within categories (e.g., tools with distinct functions) are counted (see Appendix). Next in order of importance, all with 20 or more reported uses, are Hibiscus tiliaceus, Pandanus tectorius, Calophyllum inophyllum, Cordia subcordata, Guettarda speciosa, Scaevola sericea, Pemphis acidula, Thespesia populnea, Rhizophora spp., Tournefortia argentea, Casuarina equisetifolia, Premna serratifolia, Morinda citrifolia, Pipturus argenteus, Terminalia catappa, Ficus tinctoria and Ficus prolixa. Another 29 species have at least 7 uses each (Table 2). There is some usage overlap between categories, such as supplementary and emergency foods and medicinal plants, magical, ceremonial and body ornamentation plants, or plants used for handicrafts, woodcarving, cordage, and clothing. Conversely, the categories could be further broken down to yield an even greater list of uses (e.g., 125 for coconut). Moreover, the list does not include the more strictly ecological functions of coastal plants, such as shade, protection from wind, sand and salt spray, erosion and flood control, coastal reclamation, animal and plant habitats, and soil improvement, all of importance to Pacific societies.

In terms of specific uses, the most widely reported uses are for medicine, general construction, body ornamentation, fuelwood, ceremony and ritual, cultivated or ornamental plants, toolmaking, food, boat or canoe making, dyes or pigments, magic and sorcery, fishing equipment, cordage and fibre, games or toys, perfumes and scenting coconut oil, fertilizer and mulching, woodcarving, weapons or traps, food parcelization, subjects of legends, mythology, songs, riddles, and proverbs, domesticated and wild animal feed, handicrafts, cooking equipment, clothing, fish poisons, items for export of local sale, adhesives or caulking, and musical instruments, all of which were reported for at least eleven species (Table 1). The analysis, however, is based on traditional uses, many of which have lapsed or are only employed in emergency, because modern technology has pre-empted them.

In terms of plant type, trees have the greatest utility, both in numerical dominance and diversity of uses per tree, with 671 purposes or uses reported for 62 species, an average of 10.8 uses per species (Table 1). Next in importance are shrubs, with 159 uses for 26 species, an average of 6.2 uses per species, followed by vines and lianas, herbs, ferns, and grasses, with averages of 4.4, 3.7, 3.5 and 2.9 uses per species respectively.

Medicinal Plants

The most frequently reported use of coastal plants is medicinal, with 113 species (81%) reportedly used medicinally, in at least one area of the Pacific. The medicinal importance of these same species in the ancestral homeland of Pacific peoples is supported by the fact that 109 of the

total of 140 species or closely related species are used for medicinal purposes in southeast Asia (Perry and Metzger, 1980).

Of the 113 species reportedly used medicinally, almost a quarter of these (27) are used medicinally for a variety of purposes, wherever they are found throughout the Pacific, as well as in southeast Asia (Perry and Metzger, 1980). Among the species of most widespread medicinal importance are Polypodium scolopendria, Triumfetta procumbens, Cassytha filiformis, Vigna marina, Wollastonia biflora, Cocos nucifera, Glochidion spp., Guettarda speciosa, Hibiscus tiliaceus, Morinda citrifolia, Pandanus tectorius, Premna serratifolia, Terminalia catappa, Vitex spp., and Xylocarpus spp.

The relative importance of coastal plants as a percentage of total medicinal plant resources ranges from around 20% for the larger high islands of western Melanesia to a high of 67 to 82% for the smaller atolls and limestone islands of Kiribati and Nauru (Table 3). Moreover, the proportion of coastal medicinal plants as a percentage of all medicinal plants would have been considerablly higher prior to European contact, particularly on the smaller islands, because many of the medicinal plants of today are recent introductions which have been adopted for medicinal use.

Also of medicinal value are species used as insect repellants or fumigants, soap substitutes, shampoos or hair conditioners, and antitoxins. Of the soap substitutes, Colubrina asiatica, is used almost universally for this purpose. Among those used for antitoxins, as insect repellants, or to treat puncture wounds from marine animals or jellyfish stings are Avicennia maritima, Cassytha filiformis, Crinum asiaticum, Excoecaria agallocha, Sophora tomentosa, and Tournefortia argentea, whereas the seeds of Calophyllum inophyllum, the heartwood of Santalum yasi, and the leaves of Vitex spp. are burned as mosquito repellents. Several species are also used to fumigate clothing (Appendix).

General Construction

The timber of 60 species (6 shrub and 54 tree species), 43% of all coastal species and 87% of all tree species, was reportedly used for general construction purposes such as sawn or hewn timber, house poles, beams, rafters, flooring, walling, pilings, wharves, bridges, etc. Some of the more commonly used species include Bruguiera gymnorhiza, Calophyllum inophyllum, Casuarina equisetifolia, Cocos nucifera, Guettarda speciosa, Heritiera littoralis, Hibiscus tiliaceus, Inocarpus fagifer, Intsia bijuga, Lumnitzera littorea, Pandanus tectorius, Rhizophora spp., Terminalia catappa, and Thespesia populnea. Shrubby species such as Pemphis acidula and Scaevola sericea are important for house frames and planking on atolls. Of particular importance for thatching are Cocos nucifera, Metroxylon spp., Nypa fruticans, and Pandanus spp.

Fuel

Although most woody species are used for fuel, some are particularly favoured, because of their high heat content, ability to produce slow-burning charcoal or provide a desired taste to foods, or in some cases to cook things particularly slowly. These include the shrubs, Pemphis acidula and Suriana maritima, because of the hot flame they produce. Among the trees, the mangrove species, Bruguiera gymnorhiza and Rhizophora spp., are preferred firewood in many coastal areas and also used to produce charcoal commercially in Fiji. Casuarina equisetifolia and Calophyllum inophyllum are excellent firewoods, and almost all parts of the coconut palm are used for fuel, with the shells of the nuts being a preferred fuel and an excellent source of charcoal. The coconut palm is by far the main source of fuel in atoll countries, as well as on some of the larger low-lying islands such a Tongatapu in Tonga (Thaman, 1984). Premna serrratifolia, is considered

the best wood for cooking pandanus in the earthen oven in Nauru, and Hibiscus tiliaceus is a decent firewood, especially for slow smoking, and seems to be particulary suited for firing bakery ovens, such as on Aitutaki, in the Cook Islands, where it is used for that purpose. Certain species are also favored for making fire by friction and for use as tinder (Appendix).

Canoe and Boat Building

The diversity and sophistication of ocean transport ranging from the multiple-hulled lakatoi of the Papuan Gulf and the elaborate double-hulled chiefly voyaging, and war canoes of Polynesia and Micronesia, to smaller fishing and racing outrigger canoes and freight rafts, with and without sails, made possible the migration to and settlement of vast stretches of the Pacific Ocean (Haddon and Hornell, 1975). Without such sophisticated voyaging technology, the great hiri and Kula Ring trade networks of Papua New Guinea, the trade networks between Fiji, Tonga, and Samoa, as well as the great interisland voyaging and tuna fishing, so important in Micronesia and the smaller islands of Polynesia, would not have been possible. The components of such craft, almost all of which are derived from plants, included hulls, keel and prow pieces, floats or outriggers, booms, ribs and spreaders, garboard strakes and gunwhales, planking, platforms, shelters and elaborate decking, masts, paddles and steering oars, sails and weather screens, all bound together, primarily with coconut husk fiber cordage, and caulked with plant materials.

Some 34 species, including over 48% of all trees, were used in canoe or boatbuilding. Particularly valued for canoe hulls or keel pieces were Calophyllum inophyllum, which was favored for the hulls of the larger Polynesian chiefly and voyaging canoes such as the tipairua of Tahiti and for the keel piece of Kiribati canoes; Cordia subcordata in the northern Cook Islands, Tuamotus, and Kiribati; coconut for some smaller canoe hulls or for planking in the Tuamotus and Kiribati; and Serianthes in Fiji and Palau. In the Tuamotus, where Cordia was favored, after a cyclone had destroyed the remaining Cordia groves, canoe builders had to turn to Pisonia grandis, a canoe hull which will only last two years, whereas a Cordia hull will last 30 to 40 years (Haddon and Hornell, 1975). In Tuvalu, Hernandia sonora was favored for canoe hulls and for the multiple floats of freight rafts used for transporting large loads of coconuts or timber across lagoons from reef islets to main settlements (Koch, 1983).

Species favored for other components, such as keel pieces, cross beams, pegs or connectives, and floats or outriggers include Pemphis acidula, Guettarda speciosa, Hibiscus tiliaceus, and Tournefortia argentea. In Fiji, the upper mast or domodomo of the large travelling outriggers or camakau, of up to 100 feet in length, were always made with Intsia bijuga. Woods such as Calophyllum inophyllum were favored for bailers; sails were plaited from pandanus and coconut leaves; and other species used as adhesives and for caulking (Haddon and Hornell, 1975).

Other Uses of Timber and Wood

Other common uses of timber and the woody parts of plants include toolmaking, woodcarving, and the production of fishing equipment, weapons and traps, cooking equipment, games or toys, musical instruments, animal pens or roosts, and a wide range of other handicrafts (Table 1).

Species preferred for tools, such as digging sticks, needles and awls, adze and tool handles, tapa beaters and anvils include durable shrubby species such as Pemphis acidula, Suriana maritima, and Ximenia americana, and trees such as Bruguiera gymnorhiza, Calophyllum inophyllum, Casuarina equisetifolia, Cocos nucifera, Cordia subcordata, Inocarpus fagifer, Rhizophora spp., Terminalia catappa, and Thespesia populnea, with softer-wooded species such

as Erythrina variegata, Guettarda speciosa, Hibiscus tiliaceus, and Tournefortia argentea, being locally important, particularly on atolls.

Essentially the same species are favored for producing weaponry, such as warclubs, spears and spearpoints, with more specialized items such as bows being made from Colubrina asiatica and Bruguiera gymnorhiza; arrows from Nypa fruticans leaf midribs and the stiltroots of Rhizophora spp.; and snares for capturing fruitbats (flying foxes) and birds from the thorny stems of Caesalpinia spp.

A similar range of species is favored for fishing poles, fishtraps, fish hooks, fishnet frames and handles, nets, meshing needles, floats, and other fishing equipment, with Dodonea viscosa, Cordia subcordata, Guettarda speciosa, Hibiscus tiliaceus, Premna serratifolia, Thespesia populnea, and Vitex spp. being used for fishing rods or hoists; the extremely strong wood of Pemphis acidula for fishhooks, with the wood of Premna serratifolia, the roots of Casuarina equisetifolia, and the thorny sections of Caesalpinia bonduc being used for specialized fishhooks; Ficus tinctoria, Dodonea viscosa, and Rhizophora spp. for scoopnet frames; Cocos nucifera (roots), Lumnitzera littorea, Pemphis acidula, and Rhizophora spp. for fishtraps or cages; lighter woods such as Dolichadrone spathacea, Erythrina variegata, Hernandia sonora, and Hibiscus tiliaceus for floats and paddles; and the bast fiber from Ficus spp., Hibiscus tiliaceus, Pandanus tectorius, and Pipturus argenteus being used to make nets, with large seines made of F. prolixa in Tahiti being 30 to 40 fathoms long and twelve fathoms deep (Oliver, 1974). More specialized uses included the use of coconut fronds for weirs and long drags used in communal fish drives, fronds of Nypa fruticans as floating "fish aggregation devices" (FAD), Rhizophora spp. for shark rattles, and Cordia subcordata and Hibiscus tiliaceus to make buoyant watertight "reefboxes" or toluma (Tokelau) used to store valuable fishing gear such as pearlshell fishing lures.

Similar species are favored for cooking equipment such as bowls, calabashes, ladles, stirrers, mortars and pestles, coconut huskers, and breadfruit splitters and specialized containers, with Hernandia sonora and Sonneratia alba and coconut husk being used for corks or stoppers. Coconut shells are used universally for cups, containers, spoons, with other parts being used for a wide range of cooking equipment (Appendix).

For toys and games the seeds or fruit of Entada phaseoloides, Mucuna gigantea, Abrus precatorius, Caesalpinia bonduc, Barringtonia asiatica, Cynometra ramiflora, Erythrina variegata, Hernandia sonora, Thespesia populnea and Xylocarpus spp. are used for marbles, lagging pieces, small balls, tops and for a range of other toys or games, with the fruit of Ficus tinctoria and chewed pieces of coconut endosperm or pandanus prop roots being used for ammunition for toy blowguns made from a hollowed-out Scaevola sericea stem. The wood of Gardenia taitensis is carved into marbles and cricket balls in Tuvalu, and the wood of other species used to make darts, sticks for jackstraws and other stick games, tops and other toys, while the stems of Cyperus laevigatus are used as cordage for string games or "cat's cradle", coconut and pandanus leaves plaited into balls for kicking or throwing games, pandanus leaves are made into kites, and parts of the coconut palm are made into a range of toys (Appendix).

The most favored species for musical instruments, mainly drums or slit-gongs, include Pemphis acidula, Cocos nucifera, Guettarda speciosa, Lumnitzera lirrorea, Terminalia catappa, and Thespesia populnea, with the fruit of Bruguiera gymnorhiza and Rhizophora spp. and the leaves of Pandanus tectorius being used for whistles.

In terms of more specialized, high quality woodcarving of spiritual or prestige importance, such as idols of gods, pendants or "tiki", ceremonial kava bowls, carved prow pieces for canoes, or items for the burgeoning tourist market, certain high quality woods were generally preserved. Although some 19 species are reportedly used in woodcarving, the most highly sought after species, because of their attractive and durable wood, include, Calophyllum inophyllum, Cordia

subcordata, Intsia bijuga, Santalum spp., and Thespesia populnea, the latter four being endangered plants in many areas.

Ceremonial and Spiritual Importance

The ceremonial and spiritual importance of plants, can not be underestimated, with 40 species having ceremony or ritual importance, 29 used in magic and sorcery, and 18 featuring legends, mythology, songs, riddles, or proverbs.

Those of more ceremonial importance, include species used in ceremonies or rituals associated with death, war and peace, human sacrifice and cannibalism, circumcision or coming of age, house or temple building, canoe making and launching, fishing, planting cycles, wavemaking or control of seastate, prayer sessions, as well as species serving as symbols or totems and mediums for communicating with spirits or gods or those planted in sacred groves or burial grounds. Others are associated with times of revelry or are used in the production of baskets, mats, and other articles reserved for ceremonial exchange or dress (Appendix).

Plants of particular ritual importance include Polypodium scolopendria, Dodonea viscosa, Hibiscus tiliaceus, Calophyllum inophyllum, Cocos nucifera, Scaevola sericea, Pandanus tectorius, Sida fallax and Thespesia populnea. Plants cultivated or protected in sacred groves, in graveyards or around temples included Casuarina equisetifolia, Calophyllum inophyllum, Ficus spp., Intsia bijuga,and Thespesia populnea. Large banyans (Ficus spp.) were, and still are in many places considered as the abode of spirits or aitu throughout Polynesia and Melanesia, and in Vanuatu are still found in almost all ceremonial meeting grounds or nakamal. Sacred Pisonia grandis groves are reported from Onotoa in Kiribati and its leaves considered to be gods on Tongareva (Koch, 1986; Hiroa, 1932a), and the cycad (Cycas circinalis) is of particular spiritual importance in Vanuatu where it is a symbol on the national flag and is planted around ceremonial dance grounds.

Gardenis taitensis is the national flower of both Tahiti and the Cook Islands; Sida fallax, is the flower of the island of Abemama in Kiribati and of Oahu in Hawaii, and was traditionally reserved for chiefs in both areas; Heliotroium anomalum is the flower of the Hawaiian island of Kaho'olawe; and Pandanus tectorius has become the symbol of the people of Kiribati. Casuarina equisetifolia and Premna serratifolia, are the symbols or bodily forms of the Polynesian gods Oro and Avaro in Tahiti, whereas the coconut is identified with Ku, the god of fishing, and Thespesia populnea is the shadow of the god of chanting and prayer in Hawaii and Tahiti (Oliver, 1974; Handy et al., 1972.

In Fiji, Entada phasioloides (walai) is a totem in Namosi, Pemphis acidula (gigia) in Kabara, and Inocarpus fagifer (ivi) on Moce. Cordia subcordata (te kanawa) serves as the totem of the Korongoa clan in Kiribati, and other coastal plants undoubtedly serve as totems for other groups, especially in Melanesia, where totemism is still very strong. According to Hawaiian "natural philosophy, all natural phenomena, objects and creatures, were bodily forms assumed by nature gods or nature spirits" (Handy et al., 1972).

Plants associated with revelry or ceremonial dress, are Triumfetta procumbens, Cassytha filiformis, Premna serratifolia, Sida fallax, and Tournefortia argentea, although there are many more, some of which are discussed below as plants used for garlands and ornamentation. Epipremnum pinnatum is made into ceremonial baskets used in funerals in Tonga, Pandanus spp. and Pipturus argenteus are both used in the fine mats for ceremonial exchange, and the oil from Santalum sp. and Terminalia catappa are both used to rub corpses.

Magic and sorcery, which are still very strong in the Pacific, especially in Melanesia and parts of Micronesia, with plants being integral to such practices, which include magic related to love, exorcism of evil spirits, gardening, and death. Plants used in love magic include Portulaca lutea, Triumfetta procumbens, Ipomoea macrantha, Sida fallax, Guettarda speciosa, Pandanus tectorius, and Premna serratifolia, which is used to banish fear in marriage in Kiribati. Stenotaphrum sp. and Vigna marina are used to exorcise or dispel evil spirits; Cocos nucifera and Pipturus argenteus are used in garden magic, and Morinda citrifolia is used in love, garden, and fishing magic, and to dispel evil spirits.

Some 18 plants feature prominantly in Pacific mythology, legends, songs, riddles, proverbs, and cosmogeny. As stressed by Setchell (1924), in his Ethnobotany of Samoa, plant names were given to gods or vice versa and songs and legends have developed around them and the "heroes, families, or villages, etc. they represent." One particular Samoan text of the battle of trees and stones" ennumerates between 70 and 80 tree names. There are also legends or myths relating to the introduction of various plants, or to the role of plants in the origin of the sun, fire, etc., such as the Samoan maiden Sina who buried an eel's head which grew into the first coconut, or the story of the triumph of the Samoan tatagia tree (Acacia simplex) over the Fijian banyan tree (Ficus sp.) which had previously triumphed over all the trees of Fiji (Setchell, 1924).

Body Ornamentation and Perfumery

The importance of body ornamentation and perfumery is attested to by the considerable time and expense devoted by most societies (very extravagant expenditures in the case of more affluent societies) to clothing, jewelry, perfumes, and other items of personal adornment. Pacific island societies, similarly, placed great importance on the importance of plant products for body ornamentation and perfumery, with 44% (62 of 140) of all coastal species being used in body ornamentation and 21 species used to scent coconut oil or for perfumery (Table 1).

Many places, such a Hawaii or Tahiti, are commonly associated with flower leis or sweet smelling flowers, such as the tiare Tahiti. The salusalu, kahoa and sisi, ula, and te bau, the Fijian, Tongan, Samoan, and Kiribati equivalents of the Hawaiian lei, are all of great social, ceremonial, magical or spiritual importance, with other Pacific societies having equivalent terms for such body ornamentaion. Of particular importance in eastern Polynesia and Micronesia was a range of fragrant flowers and leaves worn in slits made in the outer edge and lobes of the ear or in pierced nostrils (Koch, 1983, 1986; Oliver, 1974). Powell (1976), Bonnemaison (1985), Koch (1983), Neal (1965) and McDonald (1978) all stress the ceremonial or magical importance of body ornamentation in Papua New Guinea, Vanuatu, Tuvalu and Hawaii, with Koch (1983) noting that ornaments used for special occasions in Tuvalu are now almost exclusively made of plants because "the longer-lasting ornaments succumbed to the puritanical zeal of the Samoan missionaries." Whereas all plants valued for perfumery have a characteristic fragrance or scent, the flowers, leaves, and plant parts used in body ornamentation, apart from being favored for their fragrance, were also valued for their their bright colors, texture and consistency of form.

Species of particular importance for body ornamentation include Polypodium scolopendria, Crinum asiaticum Dodonea viscosa, Cassytha filiformis, Cordia subcordata, Ficus spp., Gardenia taitensis, Hibiscus tiliaceus, Sida fallax, and Lumnitzera littorea. Of almost ubiquitous importance were the bright orange-red fruits, the male flower, and other parts of the pandanus, which were strung into leis and garlands and the very young leaflets and other parts of the coconut which were also used in body ornamentation (Appendix).

Also of widespread importance for use in necklaces, bracelets, earrings, or dancing anklets are the seeds of a wide range of species including Abrus precatorius, Entada phasioloides, and Mucuna gigantea, with the wood of some species being occasionally carved into earings.

Of the species used to scent coconut oil, a product which remains of considerable importance for ceremonial exchange, commercial sale, and ritual, cosmetic, medicinal and other domestic purposes, the most widely used are the fragrant leaves of Polypodium scolopendria, the root nodules of Fimbrytylis cymosa, the flowers of Guettarda speciosa, and Phaleria disperma, and the male flower of Pandanus tectorius. Of particular importance are G. taitensis, which is used in the commercial production of the traditionally important "mono'i" scented coconut oil in Tahiti and Rarotonga, and the seeds and flowers of C. inophyllum and heartwood of Santalum spp., which are used in making chiefly perfumed oil used in death rituals. Forster (1777 in Oliver, 1974) of Cook's expedition, reports the use of scented coconut oil or mono'i as pomade by both sexes in Tahiti, with sandalwood and some thirteen other plants being used to scent it.

Cultivated or Ornamental Plants

Some 39 species of coastal plants are deliberately cultivated or protected in gardens due to their usefulness or ornamental value, often as living fencing or hedges (Appendix). The ferns, particularly the bird's-nest fern, Asplenium nidis, and Nephrolepis spp., and Polypodium scolopendria, are popular ornamental or house plants. Other common ornamentals include Crinum asiaticum, Dendrobium spp., Hymenocallis littoralis, Epipremnum pinnatum, and Hoya australis, among the the herbaceous species, with shrubby species Clerodendrum inerme, Gardenia taitensis, Scaevola sericea being common occurrences in houseyard gardens in many areas of the Pacific. In Hawaii, Sida fallax ('ilima) is cultivated, often commercially, for its flowers.

Tree species commonly found in cultivation in houseyard gardens include Cordia subcordata, Cycas circinalis, Erythrina variegata, Guettarda speciosa, Hibiscus tiliaceus, Morinda citrifolia, Pandanus tectorius, Terminalia catappa, and Thespesia populnea. Those also common in houseyard gardens, as well as being planted in rural garden lands as food plants, include Cocos nucifera, Ficus tinctoria, Inocarpus fagifer, Metroxylon spp., and Pandanus tectorius. In the case of the majority of these plants, deliberate selection has obviously taken place, with a number of named cultivars existing for most species, including non-food species such as C. manghas, E. variegata, and H. tiliaceus.

Species commonly planted as living fencing (with and without wiring), and as animal pens, hedging, garden borders, and boundary markers, include Clerodendrum inerme, Cocos nucifera, Erythrina variegata, Ficus tinctoria, Hibiscus tiliaceus, and Premna serratifolia, with Crinum asiaticum commonly used for garden borders. C. nucifera and Inocarpus fagifer are used for boundary markers, Cocos nucifera logs and thatching for non-living pig pens and fencing, and coconut thatch and roots used to make sand screens. On Majuro and Kwajalein in the Marshall Islands, Vitex trifolia is commonly planted as reportedly mosquito repelling hedges and windbreaks.

Food Resources

Coastal plants are a significant food resource, with some 6 species used as staple foods, 23 as supplementary foods, 35 as emergency or famine foods, 5 as drinks or beverages, 19 as domestic animal foods, and another 8 serving as food for important wild animal species. Also of critical importance are the roles that coastal vegetation, particularly mangroves, play as habitats and links in the food chains of important fisheries resources.

Of the staples, the most important is the coconut palm, the tree of life for most of the coastal Pacific, which provides an almost endless array of food items prepared in many ways

(Appendix). As Massal and Barrau (1956) argue: "Human life on atolls would scarcely be possible without it", with per capita consumptions as high as 5 to 6 nuts per day having been recorded on some atolls. The pith of the trunk of the sago palm (Metroxlon spp.), found in both wild and cultivated states, which is processed into starch, is the main staple in some coastal and riparian areas of western Melanesia and a major item of the "hiri" trade networks of the Papuan Gulf. The starch is also made into puddings and desserts in Melanesia, Rotuma and Samoa, and the heart or meristem sold and eaten in curries by Indians in Fiji. Polynesian arrowroot (Tacca leontopetaloides), formerly a minor staple in most parts of the Pacific, but now more of an emergency food, is grated, washed and cooked in green leaves in Vanuatu and in areas of Polynesia and Micronesia to make starchy puddings, and was formerly the source of starch for export from some islands (Massal and Barrau, 1956).

The mature seeds or drupes of Pandanus tectorius, or the cultivated form of P. tectorius , P. pulposus, of which there are many cultivars, are eaten raw as a vitamin-A-rich snack food throughout most of Micronesia, atoll Polynesia and parts of Vanuatu and Solomon Islands. In Micronesia and atoll Polynesia, the fruit are pounded, cooked in a variety of ways, made into flour, or preserved by smoking or sun-drying as an important staple. The tips of the aerial roots are sometimes eaten raw or cooked on atolls and the hearts or meristem are occasionally cooked as an emergency food on some Polynesian atolls (Massal and Barrau, 1956; Barrau, 1961; Manner and Mallon, 1989). The mature seeds of the Tahitian chestnut (Inocarpus fagifer) are a seasonal staple or snack food throughout most of Melanesia and Polynesia, and the fruit of Dyer's fig (Ficus tinctoria) is a major staple on the drier islands of Kiribati and a supplementary staple in other areas of Kiribati, Tuvalu and Micronesia.

Among the more commonly consumed supplementary foods are the seeds of the beach or Indian almond (Terminalia catappa), as is the flesh of the ripe fruit in some areas of Papua New Guinea and Nauru, and the extremely foetid ripe fruit of the Indian mulberry (Morinda citrifolia), which was widely eaten in the past. Also eaten more commonly in the past were the seeds and possibly the fibrous pulp of the fruit of Neisosperma oppositifolia.

Asplenium nidis, the bird's-nest fern, is eaten on many atolls and considered a delicacy in Niue, and the fruit of the mangrove species Bruguiera gymnorhiza is eaten cooked in Nauru, Palau, and Yap in Micronesia, and throughout most of Melanesia, especially in New Caledonia (Massal and Barrau, 1956; Jardin, 1984). Peculiar to Melanesia, and particularly New Caledonia, is the consumption of the young shoots, bark, and sapwood of Hibiscus tiliaceus and the fruit and leaves of Wollastonia biflora (Massal and Barrau, 1956). The purslanes, Portulaca australis and P. lutea, are widely eaten as vegetables or emergency foods in Kiribati and other atoll areas, with adults formerly eating up to a kilogram per week in the Phoenix Islands of Kiribati (Turbott, 1954).

Species consumed more as emergency foods, include the young fronds of most ferns and the leaves and tender shoots of a wide range of species including Boerhavia spp., Ipomoea pes-caprae, and Peperomia spp. (Massal and Barrau, 1956; Merrill, 1943), with T. argentea leaves being eaten in salads and by sailors on long voyages in Kiribati and P. grandis leaves being cooked and eaten with fish in Vanuatu and taro on Kapingamarangi atoll. A sterile cultivar, P. alba, is the lettuce tree of Indonesia.

The seeds of the cycad (Cycas circinalis), which are edible after thorough washing and processing into flour, were a widely consumed famine or ceremonial food in many areas, and regularly eaten on Guam. On Pentecost in Vanuatu, an edible starch was reportedly extracted from the leaf stalk of Epipremnum pinnatum (Massal and Barrau, 1956). The roots of the sedges Eleocharis spp. and Cyperus javanicus were also reportedly eaten as emergency foods, and the seeds or fruit of Avicennia maritima, Cordia subcordata, Sonneratia alba, Terminalia littoralis, and

a number of other trees, and many of the leguminous vines are occasionally eaten in some areas (Massal and Barrau, 1956; Barrau, 1961; Jardin, 1974).

Foremost among the beverage plants is the coconut palm, which provides both juice from the nut and fresh and fermented toddy from the sap of the flower spathe, the importance and ritual significance of which is greatest on the freshwater-scarce atolls. Other drinks include the sap from the nypa palm flower spathe, which is fermented into alcohol and vinegar; water from the thick vines of Entada phasioloides and Mucuna gigantea; and teas or stimulants made from a number of species (Appendix).

Also of considerable indirect value to human food systems are those species serving as domestic animal feed and food or habitats for important wild food species. Coconut is, again, the most important subsistence feed for pigs, chickens, and dogs, as well as being widely used in commercial livestock and poultry rations both locally and overseas. Other species including Portulaca, Ipomoea and Ficus spp. Scaevola sericea, Tournefortia argentea, and Boerhavia spp., are also fed to domestic livestock, with both Hibiscus tiliaceus and Pisonia grandis being planted as living pig pens, the leaves being fed directly to the animals. Those which are food sources to important wild food species such as coconut crabs, fruit bats, pigeons, and other birds, include Cocos nucifera, Ficus spp., Premna serratifolia, Scaevola sericea, Soulamea amara, Syzygium spp., and Terminalia catappa.

Of particular importance are mangrove ecosystems which contribute through primary and secondary productivity, to the nutritional requirements of a high proportion of marine food species (Watling, 1985). Research in Fiji has shown that over 60% of commercially important species are mangrove associated at some stage in their life cycle (Lal, et al., 1983), whereas more rigorous research gives figures of 67% and 80% for eastern Australia and Florida (Watling, 1985). Baines (1979) argues that mangrove removal can lead to offshore fisheries' yield declines of 50 to 80%.

Cordage and Fibre

Some 25 species were used to provide cordage or fibre for lashings on housing, boats, and weapons; fishing lines and nets; for tying parcels and stringing fish; and for a wide range of handicrafts (Appendix). Of ubiquitous importance is the husk fibre or coir of the coconut which is made into cordage and sennit throughout the Pacific (sometimes strengthened with human hair), as well as being used for straining coconut oil and liquids, stuffing and caulking, and a wide range of other uses (Appendix). Also of widespread importance are the bast fibre of Hibiscus tiliaceus and Pipturus argenteus and the leaves of Pandanus spp., which are used for lashing, cordage, and in a wide range of handicrafts, with Ficus prolixa and F. tinctoria both providing cordage for fishing nets and other purposes locally. The stems of the sedges Cyperus laevigatus and C. javanicus and the bast fiber of Hibiscus tiliaceus are used to strain kava (Piper methysticum), coconut cream, and other liquids, and dried fibrous pandanus drupes, coconut coir, and Hibiscus tiliaceus bast fibre are used for brushes for painting tapa and other purposes.

Also commonly used for cordage or lashing are the stems of the ferns Thelypteris spp. and Stenoclaena palustris; the vines Cassytha filiformis, Canavalia cathartica, Entada phaseoloides, Hoya australis, and Ipomoea pes-caprae; and the bast fiber of Wollastonia biflora, Triumfetta procumbens, and Wikstroemia spp.

Handicrafts and Clothing

Seventeen and 14 species, respectively, are used in the production of handicrafts and clothing (Table 1), The most important are the coconut palm, pandanus, and Hibiscus tiliaceus, the

leaves of the former two being used throughout the Pacific for a large range of plaited ware, including hats, skirts, waist mats, and a wide range of ceremonial and ordinary mats, with other parts, particularly the husk and shell of the coconut, also being used in a wide range of handicrafts, with the husk fiber being particularly important. The bast fibre of Hibiscus tiliaceus is used in a wide array of handicrafts, and along with pandanus, is particularly important for the highest quality ceremonial mats and garments (Hiroa, 1930; Koch, 1986).

Other species used for grass skirts, plaited ware, bark cloth and ceremonial apparel and other handicrafts include Asplenium nidus, Cyperus and Eleocharis spp., Epipremnum pinnatum, Tacca leontopetaloides, Cordia subcordata, Ficus spp., and Pipturus argenteus. The seeds of Acacia simplex, Entada phasioloides, Metroxylon spp., and Nypa fruticans being used for buttons, beads, dancing anklets and other purposes, and the leaves of Metroxylon spp. and N. fruticans for hats and other plaited ware (Appendix).

Dyes, Pigments and Tannins

Some 30 and 7 species respectively are used as dyes and pigments or tannins and preservatives (Table 1). Common uses are for dying, painting or strengthening and preserving barkcloth, mats, baskets and other plaited ware, grass skirts, breachcloths, hats and other clothing items, canoe sails, and the hair, face and other parts of the body for ceremonial occasions. Colors range from black and black-brown to red-brown, red, red-orange and yellow. Although bark is the most common source, roots, leaves, sap, flowers, fruit and seeds are also dye sources.

Of most widespread importance are Ficus tinctoria, Bruguiera gymnorhiza, Morinda citrifolia, and Rhizophora spp. Colubrina asiatica, although not technically a dye, is used to wash and whiten textile kilts and garments made from Cyphlophus heterophyllus in Samoa (Hiroa, 1930).

Fertilizers, Mulching and Soil Improvement

The importance of organic material to the success of agriculture and plant growth in nutritionally poor and highly permeable coastal soils, particularly atoll soils, which are among the least fertile in the world, cannot be overstated, with many Pacific societies having evolved sophisticated systems of fertilization and mulching using the leaves from at least 21 coastal plants. In atoll Micronesia the practice has attained the greatest sophistication. In Kiribati, the leaves of Guettarda speciosa, Tournefortia argentea and Sida fallax are often applied in pandanus baskets, with other leaves and topsoil, as part of an elaborate mulching system for giant swamp taro Cyrtosperma chamissonis, pandanus, and breadfruit (Small, 1972; Lambert, 1982; Soucie, 1983). Other less elaborate systems include the almost universal use of plaited and unplaited coconut fronds to mulch wetland taro gardens and the digging in of grasses, ferns and other leaves to maintain soil fertility and structure, preserve moisture and inhibit weed growth.

Casuarina equisetifolia is widely acclaimed for its nitrogen fixing ability, and Canavalia rosea has been planted as green manure and cover crop in Samoa.

Food Parcelization

The leaves of some 19 species are used for food parcelization. Most important are the fronds of the ferns, Thelypterus and Nephrolepis spp., and the leaves of Cocos nucifera, Guettarda speciosa and Hibiscus tiliaceus which are used to parcel seafoods and other foods for

transport, sale and cooking or for covering the food in an earthen oven before it is sealed with earth.

Fish Poisons

An important complement to the sophisticated fishing gear used by subsistence coastal societies were fish poisons or stupificants, with some 11 species being used for this purpose. The most commonly used species are Barringtonia asiatica, Derris trifoliata, Pittosporum spp. and Tephrosia purpurea, which reportedly suffocate without affecting the flesh (Merrill, 1943).

Adhesives and Caulking

Eleven species are used as adhesives, waterproofing, or caulking for canoes, housing and other products. Of most universal importance were the tubers of Polynesian arrowroot (Tacca leontopetaloides) which were used as an adhesive for tapa cloth throughout Polynesia, and the bast fibre of Hibiscus tiliaceus and coconut coir which were widely used for caulking. Other sources include the leaves of Ipomoea pes-caprae which were roasted and used for canoe caulking, the sap of Ficus spp. and Pipturus argenteus and the sap or latex from the fruit of Calophyllum inophyllum, Cordia subcordata, Inocarpus fagifer, and Rhizophora spp. (Appendix).

Other Uses

Other uses which were reported five times or less include strainers and filters, toilet paper, land reclamation, illumination, natural clocks, oils and lubricants, brushes, fans, stimulants, aphrodesiacs, contraceptives, masticants, abrasives, combs, tooth brushes, corks, cigarette wrappers, coconut palm climbing bandages or harnesses, measuring tapes, fireworks, windbreaks, sand screens, ladders, tethering posts, fish bait, punishment, communication or language, and computation or counting (Appendix).

Of particular importance are species planted for land reclamation including Bruguiera gymnorhiza, Casuarina equisetifolia, Lumnitzera littorea, Rhizophora spp. and Scaevola sericea. Finally, Mescam (1989) relates how a wide range of leaves are used to pass messages or warnings or for computation or counting in Vanuatu, but that this "botanical language" is being lost because "the written language learnt by the young has taken its place."

CONCLUSION

The ethnobotany of coastal plants provides an important key to a better understanding of the cultural sophistication and storehouse of empirical knowledge possessed by Pacific island societies. The study shows that there are at least 75 different purpose- or use-categories for the 140 coastal plant species studied, with the total number of uses being 1024, an average of 7.3 distinctive uses per plant. This diverse utility underlines the central role that coastal plants have played in the successful habitation of the Pacific islands and in providing a high degree of "subsistence affluence" (Fisk, 1972). If the more strictly ecological functions of coastal plants, such as shade, protection from wind, sand and salt spray, erosion and flood control, coastal reclamation, animal and plant habitats, and soil improvement, and their ability to live in harsh coastal environments, are also considered, the critical role of coastal vegetation in the maintenance of Pacific societies, particularly in light of the increased susceptibility of atoll and coastal areas to

extreme events, such as tsunamis, storm surge and hurricanes, which could occur due to predicted global warming (Thaman, 1989), becomes more apparent.

However, the economic, cultural and ecological value of coastal plant resources is rarely acknowledged in development plans, project documents, or aid proposals, despite the fact that the products and benefits provided by coastal vegetation would be extremely expensive or impossible to replace with imported substitutes. The elimination of such utilitarian and cultural diversity can only serve to erode "subsistence affluence and to lock Pacific societies more tightly into the vicious circle of economic and cultural dependency.

Unfortunately, centuries of exploitation and reclamation of coastal strand and mangrove forests and, more recently, urban-industrial development have led to serious coastal deforestation and the endangerment and extinction of indigenous and traditionally important coastal tree and plant species throughout the Pacific. Associated with this, and with modern institutionalized education and development planning, has been a loss of ethnobotanical knowledge and an appreciation of the subsistence and developmental importance of coastal plants. Because of the critical ecological and ethnobotanical importance, the impoverishment of these plant communities and the loss of ethnobotanical knowledge represents an ecological, economic and cultural disaster which makes more problematic the sustainable habitation of small-island states of the Pacific Ocean.

It is argued in this chapter that coastal reforestation and protection of coastal vegetation, coupled with a rejuvenation of traditional ethnobotanical knowledge, could be one of the most direct, cost-effective, self-help-oriented, and culturally-sensitive strategies for sustainable development in the small-island states and coastal areas of the tropical Pacific Ocean. The resources and the technologies already exist in the form of some 140 or more coastal strand and mangrove species of widespread ethnobotanical and ecological importance, which could be used, now, to mount village- and community-based programmes of ecological, economic, and cultural recovery and coastal reclamation which would immediately address many of the serious short-term ecological and social problems facing small island and coastal societies as well as possibly making their coastal islands and coastal areas habitable in a post-global-warming world.

Table 1. Frequency of the usage for specified purposes of 140 Pacific island coastal plant species.

Purpose/Use	Ferns x/10	Herbs x/17	Grasses /Sedges x/11	Vines/ Lianas x/14	Shrubs x/26	Trees x/62	Total x/140
Medicinal/Health	6	15	7	11	23	51	113
General Construction	-	-	-	-	6	54	60
Body Ornamentation	6	8	3	7	12	26	62
Firewood/Fuel	-	-	-	-	8	43	51
Ceremony/Ritual	3	4	-	5	6	23	41
Cultivated/Ornamental	4	3	-	2	10	20	39
Tools/Toolmaking	-	-	-	-	4	33	37
Emergency/Famine Foods	4	5	2	2	4	18	35
Boat/Canoe Building	-	-	1	-	3	30	34
Dyes/Pigments	-	-	-	2	4	24	30
Magic/Sorcery	1	6	1	1	6	14	29
Fishing Equipment	-	1	2	-	8	17	28
Cordage/Fibre	2	2	2	6	3	10	25
Games/Toys	-	-	1	4	4	16	25
Supplementary Foods	2	2	-	2	3	14	23
Scenting Oil/Perfumery	1	1	1	1	6	11	21
Fertilizer/Mulching	1	2	2	1	4	11	21
Weapons/Traps	-	-	-	-	6	14	20
Woodcarving	-	-	-	-	1	18	19
Food Parcelization	3	1	-	3	1	11	19
Animal Feed	1	4	-	3	2	9	19
Legends/Mythology	-	-	-	-	3	15	18
Handicrafts	1	1	3	2	1	9	17

Clothing	-	1	3	-	1	9	14
Musical Instruments	-	-	-	-	1	13	14
Cooking Equipment	-	-	-	-	1	12	13
Fish Poisons	-	-	-	3	4	4	11
Export/Local Sale	-	1	-	-	2	8	11
Adhesive/Caulking	-	1	-	1	-	9	11
Fire by Friction	-	-	-	-	1	8	9
Soap/Shampoo	-	1	-	3	3	2	9
Containers	-	-	-	-	1	7	8
Repellents/Fumigants	-	-	-	-	2	6	8
Wild Animal Foods	-	-	-	-	3	5	8
Tannin/Preservatives	-	-	-	-	1	6	7
Antitoxins	-	1	-	1	1	4	7
Living Fences/Hedges	-	1	-	-	1	5	7
Staple Foods	-	1	-	-	-	5	6
Drinks/Beverage	-	1	-	2	1	1	5
Strainers/Filters	-	-	2	-	-	3	5
Toilet Paper	-	-	-	-	1	4	5
Land Reclamation	-	-	-	-	-	5	5
Calendars/Clocks	-	-	-	-	-	5	5
Contraceptives/ Abortificants	-	-	-	-	3	2	5
Thatching/Roofing	-	-	-	-	1	3	4
Illumination	-	-	-	-	-	4	4
Combs	-	-	-	-	-	4	4
Animal Cages/Roosts	-	-	-	-	-	4	4
Oils/Lubricants	-	-	-	-	-	3	3
Brushes	-	-	-	-	-	3	3

Fans	-	-	-	-	-	3	3
Corks	-	-	-	-	-	3	3
Fishing bait	-	-	-	-	-	3	3
Other Uses*	-	-	2	-	5	27	34
TOTAL	35	63	32	62	161	671	1024
NO USES	-	1	1	-	-	-	2

* Other uses include stimulants/teas, flavoring/spices, ear cleaners, splints, aphrodesiacs, hair remover, masticants/chewing gum, abrasives, tooth brushes, cigarette wrappers, coconut climbing bandages or harnesses, measuring tapes, fireworks, windbreaks, sand screens, ladders, walking sticks, tethering posts, punishment/torture, communication/language, and computation or counting.

Table 2. Coastal plant species of particular cultural utility based on an analysis of different uses listed in the Appendix (Note: not including a wide range of ecological functions or uses).

Latin Name	Uses
Cocos nucifera	125
Hibiscus tiliaceus	57
Pandanus tectorius	53
Calophyllum inophyllum	43
Cordia subcordata	40
Guettarda speciosa	36
Scaevola sericea	32
Pemphis acidula	30
Thespesia populnea	26
Rhizophora spp.	25
Tournefortia argentea	23
Casuarina equisetifolia	22
Premna serratifolia	22
Morinda citrifolia	22
Pipturus argenteus	21
Terminalia catappa	21
Ficus tinctoria	21
Ficus prolixa	20
Erythrina variegata	19
Inocarpus fagifer	18
Hernandia sonora	18
Lumnitzera littorea	17
Pisonia grandis	17
Bruguiera gymnorhiza	16

Nypa fruticans	14
Barringtonia asiatica	14
Mammea odorata	14
Intsia bijuga	13
Cycas circinalis	13
Gardenia taitensis	12
Sida fallax	11
Triumfetta procumbens	11
Vitex spp.	11
Dodonea viscosa	11
Santalum spp.	10
Mammea odorata	10
Entada phasioloides	10
Cerbera manghas	10
Clerodendrum inerme	10
Cassytha filiformis	10
Tacca leontopetaloides	9
Crinum asiaticum	9
Ficus obliqua	8
Polypodium scolopendria	8
Neisosperma oppositifolia	8
Metroxylon spp.	7
Ipomoea pes-caprae	7

Table 3. Proportion of the total reported and identifiable medicinal plants constituted by coastal and mangrove plant species for selected areas of the Pacific islands.

Area	Total Medicinal Plants	Coastal Medicinal Plants	%
Melanesia	295	62	21%
Solomon Is.	145	24	17%
Fiji[1]	226	55	24%
Fiji[2]	173	57	33%
Samoa[1]	146	44	30%
Samoa[2]	77	29	38%
Tonga	71	28	39%
Kiribati	42	28	67%
Nauru	34	28	82%

Sources: Melanesia (Sterley, 1970); Solomon Is. (Maenu'u, 1979); Fiji[1] (Singh and Siwatibau, 1980); Fiji[2] (Weiner, 1984); Samoa[1] (Uhe, 1974); Samoa[2]; (Mc Cuddin, 1974); Tonga (Weiner, 1971); Kiribati (Polunin, 1979); Nauru (fieldwork by author 1978-79).

BIBLIOGRAPHY

Alkire, W.H. 1974. Numbers of plant, insect and land bird species on nineteen remote islands in the southern hemisphere. Journal of the Linnaean Society: Biology 6:143-152.

Anderson, E. 1967. Plants and man. Berkeley: University of California Press.

Baines, G.B.K. 1979. Mangroves for national development. A report on the mangrove resources of Fiji. (Unpublished manuscript).

Barrau, J. 1958. Subsistence agriculture in Melanesia. Bulletin 219. Honolulu: Bernice P. Bishop Museum.

___.1961. Subsistence agriculture in Polynesia and Micronesia. Bulletin 223. Honolulu: Bernice P. Bishop Museum.

Bellwood, P. 1978. Man's conquest of the Pacific: The prehistory of southeast Asia and Oceania. Auckland: William Collins.

Bonnemaison, J. 1985. The tree and the canoe: Roots and mobility in Vanuatu societies. In Mobility and identity in the Pacific, ed. M. Chapman. Special issue of Pacific Viewpoint 26(1):30-62.

Brown, E.D.W. 1931. Polynesian leis. American Anthropologist 33(4):615-619.

Brownlie, G. 1977. The Pteridophyte flora of Fiji. Beihefte Zur Nova Hedwigia. Heft 55. Vaduz: J. Cramer.

Bryan, E.H. Jr. 1972. Life in the Marshall Islands. Honolulu: Pacific Science Information Center, Bernice P. Bishop Museum.

Catala, R. L. A. 1957. Report on the Gilbert Islands: Some aspects of human ecology. Atoll Research Bulletin No. 59:1-187.

Chambers, A. 1975. Nanumea report: A socio-economic study of Nanumea atoll, Tuvalu. Victoria University of Wellington rural socio-economic survey of the Gilbert and Ellice Islands. Wellington: Department of Geography, Victoria University.

Christophersen, E. 1927. Vegetation of Pacific equatorial islands. Bulletin 44. Honolulu: Bernice P. Bishop Museum.

Decker, B.G. 1971. Plants, man and landscape in Marquesan valleys, French Polynesia. (Ph.D thesis. Department of Geography, University of California, Berkeley). Ann Arbor: University Microfilms International.

Fischer, J.L. and Fischer, A.M. 1970. The Eastern Carolines. New Haven: Human Relations Areas Files Press.

Fisk, E.K. 1972. Motivation and modernization. Pacific Perspective 1(1):21-23.

Flenley, J.R. and King, S.M. 1984. Late Quaternary pollen records from Easter Island. Nature 307:47-50.

Forster, J.R. 1777. A voyage round the world on His Britannic Majesty's sloop Resolution, commanded by Captain James Cook, during the years 1772, 3, 4 and 5. Vol. II. London: B. White, J. Robson, P. Elmsly, and G. Robinson.

Fosberg, F.R. 1960. The vegetation of Micronesia. Bulletin of the American Museum of Natural History 119(1):1-75.

Fosberg, F.R., Falanruw, M.V.C. and Sachet, M.-H. 1975. Vascular flora of the Northern Marianas Islands. Smithsonian Contributions to Botany. No. 22. Washington D.C.: Smithsonian Institution.

Fosberg, F.R., Otobed, D., Sachet, M.H., Oliver, R.L., Powell, D.A. and Canfield, J.E. 1980. Vascular plants of Palau with vernacular names. Washington D.C.: Department of Botany, The Smithsonian Institution.

Fosberg, F.R. and Sachet, M.-H. 1984. Micronesian Poaceae: Critical and distributional notes. Micronesica 18(2): 45-120.

___. 1987 Flora of the Gilberts, checklist. Atoll Research Bulletin. No. 29:1-30.

Fosberg, F.R., Sachet, M.-H., and Oliver, R. 1979. A geographical list of the Micronesian dicotyledonae. Micronesica 15(1-2):41-295.

___. 1982. Geographical checklist of the Micronesian Pteridophyta and gymnosperms. Micronesica 18(1):23-82.

Gowers, S. 1976. Some common trees of the New Hebrides and their vernacular names. Port Vila: Forestry Section, Department of Agriculture.

Grimble, A. 1933. The migration of the pandanus people. Journal of the Polynesian Society 42 (Memoir supplement):1-84.

___. 1934. The migration of the pandanus people. Journal of the Polynesian Society 43 (Memoir supplement):85-112.

Guerin, M. 1982. The flora of the atolls of French Polynesia. In Regional technical meeting on atoll cultivation, Papeete, Tahiti, French Polynesia, 14-19 April 1980: Collected papers, ed. M. Lambert, pp. 77-89. Technical paper no. 180. Noumea: South Pacific Commission.

Haddon, A.C. and Hornell, J. 1975. Canoes of Oceania. Bernice P. Bishop special publications 27, 28, and 29. Honolulu: Bishop Museum Press.

Handy, E.S.C., Handy, E.G. with Pukui, M.K. 1972. Native planters of old Hawaii: Their life, lore, and environment. Bulletin 233. Honolulu: Bernice P. Bishop Museum.

Hedley, C. 1896. The atoll of Funafuti, Ellice Group: Its zoology, botany, ethnology, and general structure. Part 1. General account of the atoll of Funafuti. Memoir III. Sydney: Australian Museum.

___. 1897. The atoll of Funafuti, Ellice Group: Its zoology, botany, ethnology, and general structure. Part 4. The ethnology of Funafuti. Memoir III. Sydney: Australian Museum.

Hiroa, Te Rangi (Buck, P.H.). 1930. Samoan material culture. Bulletin 75. Honolulu: Bernice P. Bishop Museum.

___. 1932a. The ethnology of Tongareva. Bulletin 92. Honolulu: Bernice P. Bishop Museum.

___. 1932b. The ethnology of Manihiki and Rakahanga. Bulletin 99. Honolulu: Bernice P. Bishop Museum.

Holdsworth, D. and Mahana, P. 1983. Traditional medicinal plants of the Huon Peninsula, Morobe Province, Papua New Guinea. International Journal of Crude Drug Research 21:123-133.

Jardin, C. 1974. Kulu, kuru, uru: Lexicon of names of food plants in the south Pacific. Noumea: South Pacific Commission.

Kaaiakamanu, D.M. and Akina, J.K. (Akana, A., translator). 1922. Hawaiian herbs of medicinal value. Honolulu: Territorial Board of Health.

Kanehira, R. 1933. Flora Micronesica. Tokyo: Southseas Bureau Under the Japanese Mandate.

Kirch, P.V. 1982. Ecology and adaptation of Polynesian agricultural systems. Archaeology in Oceania 17(1):1-6.

Kirkpatrick, J.B. and Hassall, D.C. 1981. Vegetation of the Sigatoka sand dunes, Fiji. New Zealand Journal of Botany 19:285-297.

Koch, G. (G. Slatter, translator). 1983. The material culture of Tuvalu. Suva: Institute of Pacific Studies, University of the South Pacific (originally published in German in 1961 by Museum fur Volkerkunde, Berlin).

___. 1986. The material culture of Kiribati. Suva: Institute of Pacific Studies, University of the South Pacific (originally published in German in 1965 by Museum fur Volkerkunde, Berlin).

Krauss, B. No Date. Ethnobotany of Hawaii. Honolulu: Department of Botany, University of Hawaii.

Lal, P.N., Swamy, A. and Singh, P. 1983. Mangroves and secondary productivity: Fishes associated with mangroves in Wairiki Creek, Fiji. In Proceedings of an interdependent workshop, 24 February 1983, Suva, Fiji, P.N. Lal, ed. Technical report 5. Suva: Fisheries Division, Ministry of Agriculture and Fisheries.

Lamberson, J.O. 1982. A Guide to terrestrial plants of Enewetak Atoll. Honolulu: Pacific Science Information Center, Bernice P. Bishop Museum.

Lambert, M. 1982. The cultivation of `taro' (Cyrtosperma chamissonis) Schott in Kiribati. In Regional technical meeting on atoll cultivation, Papeete, Tahiti, French Polynesia, 14-19 April 1980: Collected papers, ed. M. Lambert, pp. 163-165. Technical paper no. 180. Noumea: South Pacific Commission.

Lessa, W.A. 1977. Traditional uses of the vascular plants of Ulithi Atoll, with comparative notes. Micronesica 13(2):129-190.

Luomala, K. 1953. Ethnobotany of the Gilbert Islands. Bulletin 213. Honolulu: Bernice P. Bishop Museum.

McCuddin, C.R. 1974. Samoan medicinal plants and their usage. Pagopago: Department of Medicinal Services, Government of American Samoa.

McDonald, M.A. 1978. Ka lei: The leis of Hawaii. Honolulu: Topgallant Publishing.

Maenu'u, L.P. 1979. An indicative list of Solomon Islands medicinal plants. Unpublished manuscript. Suva: Pacific Collection, University of the South Pacific, Suva.

Manner, H.I. 1987. Atoll flora and vegetation. Alafua Agricultural Bulletin 12 (3):67-80.

Manner, H.I. and Mallon, E. 1989. An annotated list of the vascular plants of Puluwat Atoll. Micronesica 22(1):23-63.

Manner, H.I., Thaman, R.R., and Hassall, D.H. 1984. Phosphate-mining induced vegetation changes on Nauru Island. Ecology 65(5):1454-1465.

___. 1985. Plant succession after phosphate mining on Nauru. Australian Geographer 16:185-195.

Marshall, M. and Fosberg, F.R. 1975. The natural history of Namoluk Atoll, Eastern Caroline Islands: With identifications of vascular flora. Atoll Research Bulletin 189:1-65.

Massal, E. and Barrau, J. 1956. Food plants of the south sea islands. Technical paper no. 94. Noumea: South Pacific Commission.

Merrill, E.D. 1943. Emergency food plants and poisonous plants of the Pacific. Technical monograph 10-420. Washington D.C.: United States Printing Office.

___. 1945. Plant life of the Pacific world. New York: The Macmillan Co.

___. 1954. The botany of Cook's voyages and its unexpected significance in relation to anthropology, biogeography, and history. Chronica Botanica 14(5/6): i-iv., 161-384.

Mescarm, G. 1989. Pentecost: An island in Vanuatu. Suva: Vanuatu Extension Centre and Institute of Pacific Studies, University of the South Pacific.

Metraux, A. 1940. Ethnology of Easter Island. Bulletin 160. Honolulu: Bernice P. Bishop Museum.

Moul, E.T. 1957. Preliminary report on the flora of Onotoa Atoll, Gilbert Islands. Atoll Research Bulletin No. 57.

Neal M.C. 1965. In gardens of Hawaii. Bernice P. Bishop Museum special publication 50. Honolulu: Bishop Museum Press.

Niering, W.A. 1956. Bioecology of Kapingamarangi Atoll, Caroline Islands: Terrestrial aspects. Atoll Research Bulletin No. 49:1-32.

Okabe, M. 1940. Investigation of the medicinal plants found on the Palau islands, their virtues and popular remedies. Bulletin of Tropical Industry, Palau. No. 5. Tokyo (Translated by Hisayoshi Takeda, Dec-1952)

Oliver, D.L. 1974. Ancient Tahitian society. Vol 1: Ethnography. Canberra: Australian national University Press.

Overy, R., Polunin, I. and Wimblett, D. W. G. 1982. Some plants of Kiribati: An illustrated list. Tarawa: National Library and Archives.

Paijmans, K. 1976. Vegetation. In New Guinea vegetation. ed. K. Paijmans, pp. 23-105. Amsterdam: Elsevier Scientific Publishing Co.

Parham, B.E.V. 1971. The vegetation of the Tokelau Islands with special reference to the plants of Nukunonu Atoll. New Zealand Journal of Botany 9(4):576-609.

___. 1972. Plants of Samoa. Information series no. 85. Wellington: Department of Scientific and Industrial Research.

Parham, J.W. 1972. Plants of the Fiji Islands (revised edition). Suva: Government Printer.

Percival, M. and Wormersley, J.S. 1975. Floristics and Ecology of the Mangrove vegetation of Papua New Guinea. Botany Bulletin no. 8. Lae: Papua New Guinea National Herbarium, Department of Forests.

Perry, L.M. and Metzger, J. 1980. Medicinal plants of East and Southeast Asia: Attributed properties and uses. Cambridge: The M.I.T. Press.

Petard, P. 1986. Quelques plants utiles de Polynesie Francaise et raau Tahiti. Papeete: Edition Haere Po no Tahiti.

Polunin, I. 1979. A study of local medicinal plants, Tarawa, Kiribati. Assignment Report. Suva: Regional Office for the Western Pacific, World Health Organisation.

Powell, J.M. 1976. Ethnobotany. In New Guinea vegetation, ed. K.Paijmans, pp 106-183. Amsterdam: Elsevier Scientific Publishing Co.

Rageau, J. 1973. Les plantes medicinales de la Nouvelle-Caledonie. Travaux et Documents de l' O.R.S.T.O.M. No. 23. Paris: Editions de l'office de la Rescherche Scientifique et Technique Outremer.

Rock, J.F. 1974. The indigenous trees of the Hawaiian Islands. Lawai, Kauai, Hawaii: Pacific Tropical Botanical Garden, and Rutland, Vermont: Charles E. Tuttle.

Sachet, M.-H. 1983. Botanique de l''ille de Tupai, Illes de la Societe. Atoll Research Bulletin 276:1-35.

St. John, H. 1948. Report on the flora of Pingelap Atoll, Caroline Islands, Micronesia, and observations on the vocabulary of the native inhabitants. Pacific plant studies 12. Pacific Science 2:97-113.

___. 1973. List and summary of the flowering plants in the Hawaiian Islands. Memoir number 1. Lawai, Kauai, Hawaii: Pacific Botanical Garden.

St. John, H. and Philipson, W.R. 1962. An account of the flora of Henderson Island, south Pacific Ocean. Transactions of the Royal Society of New Zealand: Botany 1(14):175-194.

St. John, H. and Smith, A.C. 1971. The vascular plants of the Horne and Wallis Islands. Pacific Science 25:313-348.

Sauer, C.O. 1952. Agricultural origins and dispersals. Berkeley: University of California Press.

Sauer, J.D. 1961. Coastal plant geography of Mauritius. Coastal studies series vol. 5. Baton Rouge: Louisiana State University.

___. 1967. Geographic reconnaissance of seashore vegetation along the Mexican Gulf Coast. Coastal Studies Series No. 21. Baton Rouge: Louisiana State University Press.

Seemann, B. 1873. Flora Vitiensis: A description of the plants of the Viti or Fiji Islands with an account of their history, uses, and properties. London: L. Reeve.

Setchell, W.A. 1924. American Samoa: Part I Vegetation of Tutuila Island, Part II. Ethnobotany of the Samoans, Part III. Vegetation of Rose Atoll. Vol. XX (inclusive). Washington D.C.: Department of Marine Biology, Carnegie Institution of Washington.

Singh, A. and Siwatibau, S. 1980. Medicinal plants in Fiji and other Pacific islands (Preliminary results) Suva: School of Natural Resources, University of the South Pacific.

Small, C.A. 1972. Atoll agriculture in the Gilbert and Ellice Islands. Tarawa: Department of Agriculture.

Smith, A.C. 1979. Flora Vitiensis nova: A new flora of Fiji (spermatophytes only). Vol. 1. Lawai, Kauai, Hawaii: Pacific Tropical Botanical Garden.

___. 1981. Flora Vitiensis nova: A new flora of Fiji (spermatophytes only). Vol. 2. Lawai, Kauai, Hawaii: Pacific Tropical Botanical Garden.

___. 1985. Flora Vitiensis nova: A new flora of Fiji (spermatophytes only). Vol. 3. Lawai, Kauai, Hawaii: Pacific Tropical Botanical Garden.

___. 1988. Flora Vitiensis nova: A new flora of Fiji (spermatophytes only). Vol. 4. Lawai, Kauai, Hawaii: Pacific Tropical Botanical Garden.

Soucie, E.A. 1983. Atoll agriculture for secondary schools: Soils and major agricultural crops of Micronesia. Ponape: Ponape Agriculture and Trade School.

Stemmermann, L. 1981. A guide to Pacific wetland plants. Honolulu: U. S. Army Corps of Engineers.

Sterly, J. 1970. Heilpflanzen de einwohner Melanesien: Beitrage zur ethnobotanik des sudwestlichen pazifik (medicinal plants of Melanesia: Contributions to the ethnobotany of the southwestern Pacific). Hamburg: Arbeitsstelle fur ethnomedizin.

Stone, B.C. 1970. The flora of Guam. Micronesica 6 (complete):1-659.

Sykes, W.R. 1970. Contributions to the flora of Niue. Bulletin 200. Wellington: New Zealand Department of Scientific and Industrial Research.

Sykes, W.R. 1981. The vegetation of Late, Tonga. Allertonia 2(6): 323-353.

Thaman, R.R. 1976. The Tongan agricultural system: With special emphasis on plant assemblages. Suva: University of the South Pacific (published version of 1975, Ph.D thesis, University of California, Los Angeles).

___. 1982a. Deterioration of traditional food systems, increasing malnutrition and food dependency in the Pacific islands. Journal of Food and Nutrition 39(3):109-121.

___. 1982b. The foods that came first. Alafua Agricultural Bulletin 7(3):105-116.

___. 1984d. The firewood crisis and smallholder fuelwood systems on Tongatapu Island, Tonga: Present systems and development potential. PEDP report: Tonga 85-1. Suva: United Nations Pacific Energy Development Programme (UNPEDP).

Thompson, L. 1940. Southern Lau, Fiji: An ethnography. Bulletin 162. Honolulu: Bernice P. Bishop Museum.

Turbot, J. 1954. Portulaca, a speciality in the diet of the Gilbertese in the Phoenix Islands. Journal of the Polynesian Society 63(1):77-85.

Uhe, G. 1974. Medicinal plants of Samoa. Economic Botany 28(1):1-30.

Waqavonovono, M. 1980. Traditional medicine and practices: An alternative health care system for women (A case study of traditional types of healing relating to women's ailments and conditions in seven villages in Nadarivatu, Fiji). Suva: Centre for Applied Studies in Development, University of the South Pacific.

Ward, R.G. 1980. Agricultural options for the Pacific islands. In The island states of the Pacific and Indian oceans: Anatomy of development, ed. R.T. Shand, pp 23-40. Monograph no. 23. Canberra: Development Studies Centre, Australian National University.

Watling, D. 1985. A Mangrove management plan for Fiji. Phase 1. Zonation requirements and a plan for the mangroves of the Ba, Labasa and Rewa Deltas. Suva: Government Printer.

Weiner, M.A. 1971. Ethnomedicine in Tonga. Economic Botany 25(4):423-450.

Weiner, M.A. 1984. Secrets of Fijian Medicine. Berkeley: University of California.

Wester, L. 1985. Checklist of the vascular plants of the northern Line Islands. Atoll Research Bulletin 287:1-38.

Whistler, A.W. 1980a. Coastal flowers of the tropical Pacific. Lawai, Kauai, Hawaii: The Pacific Tropical Botanical Garden.

___. 1980b. The Vegetation of Eastern Samoa. Allertonia 2(2): 45-190.

___. 1983. The flora and vegetation of Swains Island. Atoll Research Bulletin No. 262:1-25.

___. 1984. Annotated list of Samoan plant names. Economic Botany 38(4):464-489.

___. 1987. Ethnobotany of the Cook Islands: The plants, their Maori names and their uses. Lawai, Kauai, Hawaii: The Pacific Tropical Botanical Garden.

___. 1988. Ethnobotany of Tokelau: The plants, their Tokelauan names and their uses. Economic botany 42(2):155-176.

Whitmore, T.C. 1966. Guide to the forests of the British Solomon Islands. London: Oxford University Press.

Wiens, H.J. 1962. Atoll environment and ecology. New Haven: Yale University Press.

Wilder, G.P. 1931. Flora of Rarotonga. Bulletin 86. Honolulu: Bernice P. Bishop Museum.

___. 1934. The flora of Makatea. Bulletin 120. Honolulu: Bernice P. Bishop Museum.

Woodroffe, C.D. 1985. Vegetation and flora of Nui atoll, Tuvalu. Atoll Research Bulletin 283:1-28.

Yen, D.E. 1971. The development of agriculture in Oceania. In Studies in Oceania culture history Vol.2., eds. R.C. Green and M. Keedy. Pacific Anthropological Records 12:1-12.

___. 1976. Agricultural systems and prehistory in the Solomon Islands. In Southeast Solomon Islands cultural history: A preliminary survey, eds. R.C. Green and J. Cresswell, pp.61-74. Bulletin 11. Wellington: Royal Society of New Zealand.

___. 1984. Aboriculture in the subsistence of Santa Cruz, Solomon Islands. Economic Botany 28(3):247-286.

___. 1980a. Food crops. In South Pacific agriculture choices and constraints: South Pacific agricultural survey 1979, eds. R.G. Ward and A. Proctor, pp. 197-234. Manila: Asian Development Bank in association with Canberra: Australian National University Press.

___. 1980b. Pacific production systems. In South Pacific agriculture choices and constraints: South Pacific agricultural survey 1979, eds. R.G. Ward and A. Proctor, pp. 73-106. Manila: Asian Development Bank in association with Canberra: Australian National University Press.

Yuncker, T.G. 1959. Plants of Tonga. Bulletin 220. Honolulu: Bernice P. Bishop Museum.

Appendix I. Nature and ecological and cultural (ethnobotanical) importance of coastal plant species of the tropical Pacific Ocean (Notes: 1) Under Latin Name, the names in parentheses are either synonyms, important closely related species, or misidentifications commonly applied to a given species; 2) Under "Habitat", O = outpost strand zone, I = inner littoral zone, M = mangrove habitats, W = coastal wetland or marshes; N = also found naturalized or wild in non-coastal habitats, and C = cultivated or planted; 3) Under "Origin", I = indigenous, A = aboriginal introduction, R = recent post-European contact introduction, and ? = status unsure; 4) Under "Importance", "Eco" = ecological importance in coastal plant communities and "Cult" = cultural importance in terms of a species' range throughout the Pacific islands or its overwhelming importance in some localities, with +++ = very important in most island groups, with multiple usage in terms of cultural importance, ++ = of considerable importance in some island groups or some important uses locally, + = present in some island groups or of some use in restricted localities, and - = of minor ecological importance or no cultural uses reported from Melanesia, Polynesia, or Micronesia).

Latin Name (synonyms/similar or important species)	Habitat	Origin	Importance: Eco	Importance: Cult

FERNS

Latin Name	Habitat	Origin	Eco	Cult
Acrostichum aureum	I,W,M	I	++	+

Young fronds eaten cooked in Fiji and Tahiti and used medicinally in Melanesia, Tonga and Tahiti

Latin Name	Habitat	Origin	Eco	Cult
Asplenium nidus	I,N	I	++	++

Occasionally planted as an ornamental; young fronds of some varieties eaten in parts of Polynesia and Micronesia and considered a delicacy in Niue; leaves used as pig feed and to wrap food for cooking in the earthen oven in Tokelau, and to line breadfruit fermentation pits in Puluwat; fronds used medicinally in New Caledonia and Samoa; shiny outer layer of midrib used to decorate small mats and other plaited ware in Hawaii; leaves used to cover tree stump during canoe-making ceremony in Hawaii

Latin Name	Habitat	Origin	Eco	Cult
Davillia solida	I,M,N,C	I	+	+

Occasionally planted ornamental; fronds used medicinally in Melanesia

Latin Name	Habitat	Origin	Eco	Cult
Nephrolepis spp. (*N. biserrata*, *N. hirsutula*)	I,M,N,C	I	++	++

Occasionally planted as an ornamental; fronds used medicinally, for body ornamentation and food parcelization; fronds used in fishing magic in Micronesia and for mulching in Tokelau

Polypodium scolopendria I,N I +++ +++
(Phymatosorus scolopendria, Microsorum scolopendria)

Occasionally planted or protected in houseyard gardens; important in death ritual in New Guinea and in religious rituals in Tahiti; fronds used to scent coconut oil and in garlands, ear slits and body ornamentation in Melanesia, Polynesia, and Micronesia; roots, stems and fronds used medicinally in Melanesia and Polynesia; fronds used in food parcelization and to line earthen oven; young fronds eaten in New Guinea

Pteris spp. I,N I + +
(P. tripartita, P. pacifica, P. ensiformis, P. comans)

Occasionally planted or protected as an ornamental; fronds used medicinally in Melanesia and Polynesia; fronds used in head garlands in Samoa and Puluwat

Pyrrosia adnascens I,N,M I + +

(Cyclophorus adnascens, Polypodium adnascens)

Used medicinally in Fiji

Stenochlaena palustrus I,N,M,W I + +

Young fronds eaten in Fiji; long fibrous stems used for binding timber and thatch in Tonga

Tectaria spp. I,N I + +
(T. latifolia)

Young fronds eaten in Fiji; fronds and shiny black frond midribs used for decorations

Thelypteris spp. W,I,N I ++ +
(T. invisa, Cyclosorus invisa, Dryopterus invisus)

Young fronds of some species eaten cooked and raw and used for parcelization of jellyfish and seafoods; fronds used medicinally and in garlands and for body ornamentation; stems used for lashings in New Guinea

HERBS

Achyranthes spp. (A. aspera, A. canescens, A. velutina)	I	A?	+	++

Commonly protected in gardens and ruderal sites; important medicinal plant in Melanesia, Polynesia and Melanesia; used in magical songs in Puluwat

Boerhavia spp. (B. repens, B. diffusa, B. tetrandra)	O,I	I	+	++

Tuberous root a famine food in parts of Polynesia and Kiribati; used as pig feed in Kiribati; roots and leaves used medicinally in New Caledonia, Samoa and Tokelau; stems sometimes used in garlands in Tokelau; used in magic and compost in Kiribati

Crinum asiaticum	O,C	I?,A?,R	+	++

Planted in houseyard gardens, as borders, and in cemeteries; leaves used for body ornamentation for dance and worn in ear slits; leaves used to cover hot stones before placing food in earthen oven and to cover earthen oven; leaves and flower stalk used medicinally; used to treat stonefish poisoning in Micronesia; flowers used in garlands and in the hair in Kiribati, Nauru and Tuvalu; leaves used to counteract sorcery and skin of trunk to lure fish in trolling in Micronesia

Dendrobium spp. (D. tokai, D. valpelianum)	I,M,N,C	I	+	+

Occasionally planted as an ornamental; used medicinally in Fiji and New Guinea; used in personal adornment in New Guinea

Hedyotis spp. (H. biflora, Oldenlandia biflora, H. foetida, H. romanzoffiensis)	O,I	I	+	+

Used medicinally in Micronesia; fruit sometimes used in garlands in Tokelau

Heliotropium spp. (H. anomalum, H. indicum, H. procumbens)	O,I	I	+	+

Official flower of the island of Kaho'olawe in Hawaii; used medicinally in Tahiti; used to brew tea in Hawaii; stems and flowers used in garlands in Hawaii

Hymenocallis littoralis	O,I,C	R	+	+

(_Pancreatum littorale_)

Occasionally planted ornamental; flowers used in garlands in Kiribati and Nauru; leaves used medicinally and roots to counteract black magic in Pohnpei

Laportea ruderalis (_Fleurya ruderalis_)	I,N	I	+	+

Leaves and entire plant used medicinally

Lepidium bidentatum	O	I	+	+

Leaves edible; used medicinally in Tahiti

Peperomia spp.	O,I,N	I	+	+

Used medicinally in Melanesia, Tahiti and Guam; leaves eaten in New Caledonia

Portulaca lutea	O	I	+	+

Stems, leaves and roots an emergency and pig food in Micronesia; cooked after washing in sea water or mixing with toddy in Kiribati

Portulaca australis (_P. samoensis_)	O,I	I?	+	++

Stems and leaves occasionally cooked or eaten raw in Micronesia; stems and leaves pounded and mixed with coconut syrup to make pudding in Nauru; emergency food in Polynesia; common pig feed; leaves and stems used medicinally in Hawaii, Kiribati and Nauru; used in love magic in Kiribati

Procris pedunculata (_Elatostema pedunculatum_)	O,I,N	I	+	+

Small fruit reportedly edible and eaten in Tokelau; used medicinally in the Marquesas

Sesuvium portulacastrum	O,W	I	+	+

Used medicinally in New Caledonia; edible boiled or raw; used for pig feed in Kiribati

Tacca leontopetaloides	O,I,N,C	A	+	++

Occasionally cultivated in Polynesia and Micronesia; tubers cooked as a minor seasonal staple; root grated and washed to make starch and pudding and as an adhesive in Nauru and as the traditional adhesive for bark (tapa) cloth throughout Polynesia; starch formerly exported from Polynesia; fibers from flower stalk used in parts of Polynesia and Micronesia for weaving hats and fishing line; root and sometimes stems used medicinally in New Caledonia, Fiji, Tahiti, Hawaii, Nauru and Puluwat; occasionally used for garlands and scenting coconut oil in Kiribati

Taeniophyllum fasciola	I,N	I	+	-
Triumfetta procumbens	O	I	+	++

Bast fiber used for making cordage and fiber for plaited ware in Melanesia, eastern Polynesia and Micronesia; leaves, stems, flowers and burrs used medicinally; leaves used to cover or dampen fire when smoking skirts in Tuvalu; used for love and fishing magic in Micronesia and to defog diving goggles/face masks; used in compost and to make an infusion to get rid of bad breath after eating shark in Kiribati; associated with periods of revelry in Kiribati; flowers and stems used for head garlands in Tuvalu, Kiribati and Puluwat; bark used as shampoo and laundry soap in Tokelau

GRASSES AND SEDGES

Cyperus javanicus (Mariscus javanicus)	O,I,W,N	I,A,R	++	++

Fibrous stems used to strain fluids like kava in Hawaii and eastern Polynesia and for grass skirts in Kiribati, and to strain coconut oil in Hawaii; stems used to string fish and garlands in Nauru; bottoms of stems eaten as a famine food during World War II in Nauru; flower used in garlands in Kiribati

Cyperus laevigatus	W	I,A?	+	++

Stems used to make fine mats in Hawaii and skirts in Kiribati; stems used medicinally and to strain kava and other liquids in Hawaii, and for cordage and in string-figure or cat's cradle games in Kiribati

Cyperus polystachyos	O,I,W	I	+	-

No reported use

Eleocharis spp. (*E. dulcis*, *E. geniculata*)	W	I,A?	+	++

Stems used to make ceremonial fine mats in Fiji and Tonga, soft sleeping mats in Samoa, and canoe sails in Fiji; tuber of *E. dulcis* edible

Fimbristylis cymosa (*F. atollensis*)	O,I	I	++	+

Root nodules used to scent coconut oil in Tonga and Fiji; leaves and roots used medicinally in Micronesia and Tokelau; used to make fish lures in Micronesia; stems used to clean ears in Tokelau

Ischaemum murinum (*I. foliosum*, *I. longisetum*)	O	I?	+	+

Used medicinally in New Caledonia

Lepturus repens	O	I	++	+

Stems used medicinally and to clean ears in Tokelau

Paspalum distichum (*P. vaginatum*)	O,W	I,A?	+	+

Used medicinally in Fiji and New Guinea; buried as fertilizer in Puluwat

Sporobolus virginicus	O,I	I,A,R?	+	+

Buried as fertilizer in Puluwat

Stenotaphrum spp. (*S. micranthum*, *S. secundatum*)	O	I,A?	+	+

Believed by the Hawaiians to exorcise evil spirits; stems and ashes of stems used medicinally in Hawaii

Thuarea involuta	O	I	++	+

Used medicinally and to make small fish traps in Micronesia

VINES AND LIANAS

Abrus precatorius	I,M	A	+	+

Leaves, roots and seeds used medicinally in Melanesia; used for fish poison in Samoa; attractive red and black seeds used in necklaces, for children's games, and to decorate oracle boxes in Fiji

Canavalia cathartica (*C. microcarpa*)	I,N	I,R	+	+

Stems used for house lashings in Fiji; leaves and stems used medicinally in Micronesia; flowers and seeds made into leis and necklaces in Hawaii and Micronesia

Canavalia rosea (*C. maritima*)	O,I,N,C	I,R	++	++

Used as a cover crop for cocoa, bananas, coffee and other tree crops in Samoa; used as fertilizer and mulch in Puluwat; leaves and roots used medicinally in Melanesia and Tonga; used in fishing rituals in New Guinea

Canavalia sericea	O	I	+	+

Used medicinally in New Caledonia

Cassytha filiformis	O,I,N	I	++	++

Used for sorcery in Kiribati and fruit used in fishing magic in Ulithi; stem used for fastening roofing in Papua New Guinea; important medicinal plant in Melanesia, Polynesia and Micronesia; used to treat jellyfish stings in Fiji; fruit eaten by children in Micronesia and used as a premasticated infant food in Ulithi; fruit used by children as ammunition for popguns in Puluwat; sap from stems used as a shampoo and hair conditioner in Tokelau; plant used to line earthen oven in Truk; entire plant used as casual head garlands for picnics and other light-hearted occasions; tips occasionally used for scenting coconut oil in Nauru

Derris trifoliata	O,I,M	I	++	++

(_D. ulignosa_)

Extract of roots used as a fish poison in Melanesia and Polynesia; stem fibers used for cordage in the past in Tonga and vines as ropes for coconut frond leaf sweeps for communal fish drives; stems and leaves used medicinally in Melanesia and Polynesia

Entada phaseoloides I,N I ++ +++

Important totem in some parts of Fiji; drinking water obtained from thick stems; young stems used for cordage or rope; large stems used as ropes to attach coconut fronds for communal fish drives; large flat dark brown seeds used in necklaces, dance anklets, rattles, and other body ornamentation, in handicrafts, and as objects to be tossed or lagged in children's games; roots, stems, and leaves used medicinally in Melanesia and Polynesia; seeds eaten in Vanuatu and roasted and eaten with wild yams as a chiefly food offering in Fiji

Epipremnum pinnatum I,N I + ++
(_E. mirabile_, _Rhaphidophora pinnata_)

Occasionally planted as an ornamental; long slender stems used in the weaving of ceremonially important baskets in Tonga; stem, leaves and sap used medicinally in Melanesia and Polynesia

Hoya australis I,N I,R + +

Occasional as a planted ornamental; leaves and stems used medicinally in Melanesia and Polynesia; flowers used in garlands in Tonga and Samoa; stems used for lashing in New Guinea

Ipomoea littoralis O,I,N I ++ +

Flowers, stems and leaves used medicinally in eastern Polynesia and Micronesia; young leaves and stems cooked as a vegetable in Fiji and eaten raw and cooked in Micronesia, usually as an emergency food; used as a pig feed in Puluwat; flowers used occasionally in garlands in Micronesia; leaves used in love magic in Puluwat

Ipomoea macrantha O,I,N I ++ ++
(_I. tuba_. _I. grandiflora_)

Leaves crushed to produce shampoo in Kiribati; used medicinally in Samoa, Tokelau, Kiribati and Ulithi; used in love magic, for pigfeed, and the leaves for dying pandanus in Kiribati; leaves used for food parcelization in Micronesia

Ipomoea pes-caprae (I. brasiliensis)	O,W	I	+++	++

Used ceremonially in childbirth rites, in bewitching and in surf riding ceremonies to "whip up the waves" in Hawaii; roots and stems a famine food in Tahiti, Hawaii and Easter Is.; leaves, stems, roots and seeds used medicinally throughout the Pacific; stems used for lashing in Papua New Guinea; roasted leaves used for caulking canoes in Fiji

Mucuna gigantea	I,N	I	+	+

Used medicinally in Melanesia; thick vines occasionally cut to acquire water; seeds used to make necklaces and in children's games; seeds eaten in Fiji

Vigna marina	O,I,C	I	+++	++

Important medicinal plant in Melanesia, Polynesia and Micronesia; used to exorcise evils spirits (dispel fits); crushed leaves used to bathe young girls hair in Nauru; leaves used to cover the earthen oven in Nauru; leaves an ingredient in black dye on Ifaluk; leaves used for fodder in Fiji

SHRUBS

Abutilon spp. (A. indicum, A. asiaticum)	I,N,C	I	+	++

Occasionally planted in houseyard gardens; leaves and roots used medicinally in New Caledonia; young leaves and growing tips used to scent coconut oil in Nauru; flowers used in garlands Kiribati and Nauru; leaves used in mulching in Kiribati

Acanthus ilicifolius (A. ebracteatus)	M	I	+	+

Flowers and leaves used medicinally in Solomon Islands

Allophylus timoriensis (A. cobbe)	I,N	I	+	+

Wood used to make lean-to shelters, fishtraps and firewood in Micronesia; bark, leaves and buds used medicinally in Melanesia and Micronesia; seeds used for fish poison in New Caledonia

Bikkia tetrandra	O	I	+	+

(*B. grandiflora*)

Fragrant white flowers used in garlands

Caesalpinia spp. I,N,M I + ++
(*C. bonduc*, *C. crista*, *C. major*)

Thorny steams used to make snares for fruit bats and birds in Western Polynesia; thorny parts used for fishhooks on Easter Is.; bast fiber used for fastening canoe pieces and house poles; seeds and other parts used medicinally in Melanesia and Polynesia; seeds used in necklaces and for marbles

Canthium spp. I,N I + ++
(*C. odoratum*, *C. barbatum*, *Psydrax odorata*)

Durable wood used for light construction and handicrafts; wood used for digging sticks in Vanuatu and Hawaii; used medicinally in Tahiti and the Marquesas; flowers used in garlands in Tonga and Hawaii

Capparis cordifolia O,I I + +
(*C. sandwichiana*)

Occasionally planted as an ornamental; crushed as a fish poison in Nauru; used medicinally and in garlands in Hawaii

Clerodendrum inerme O,I,M,C I +++ ++

Planted as a hedge plant; wood used in frames for fishing nets and soil sieves and in shark rattles in Kiribati; branches used for fish traps in Micronesia; occasionally used as firewood; leaves, bark and sap used medicinally throughout the Pacific; leaves used with other plants as an abortifacient in Pohnpei; flowers used in garlands in Polynesia and Micronesia; leaves boiled with pandanus leaves to dye them brown in Kiribati; flowers used in love magic in Puluwat

Colubrina asiatica O,I,N I ++ ++

Branches used to make bows in Samoa; leaves woven into garlands in Nauru; very important medicinally throughout the Pacific; bark and leaves used as a soap substitute; used to wash and whiten fine white textile kilts and garments made from *Cypholophus heterophyllus* in Samoa

Desmodium umbellatum I,N I + +

Small branches used occasionally for outrigger braces; occasionally used as firewood; bark used as a soap substitute; used medicinally in Melanesia

Dalbergia candenatensis I,M I + +
(D. monosperma)

Attractive red seeds used as beads; roots and leaves used medicinally in Fiji; leaves used as fish poison in Fiji

Dodonea viscosa I,N I,A,R ++ ++

Important in death ritual in New Guinea; durable and pliable timber and branches used in house construction, for digging sticks, weapons, fishing rods, frames for scoopnets and noddy bird nets, switches, poles and other objects; occasionally used as firewood; leaves used medicinally in Melanesia and Polynesia; flowers, seed capsules, and fruit used in garlands in Hawaii and Kiribati; leaves to scent coconut oil in Kiribati and Nauru

Eugenia rariflora O,I I + +
(E. reinwardtiana, Jossinia rariflora, J. reinwardtiana)

Leaves used medicinally in Tonga; fruit edible

Euphorbia chamissonis O I + +
(E. atoto, Chamaesyce atoto)

Buds, leaves and milky sap used medicinally in Polynesia and Micronesia

Gardenia taitensis I,C I,A,R + ++

Widely planted ornamental; planted near graves of chiefs in Tuvalu; national flower of Tahiti; features in legends and songs in Polynesia and Micronesia; used in love magic and sorcery in Tuvalu; wood carved into bows and cricket balls in Tuvalu, and netting needles and gauges in Tokelau; fragrant white flowers used in leis and garlands and worn in slits in, and behind the ear and in the hair; flowers and fruit used for scenting coconut oil, which is produced commercially in Tahiti and Rarotonga; leis and head garlands sold and exported from Tahiti and Hawaii; used medicinally in Melanesia and Polynesia; selected cultivars recognized in Polynesia

Geniostoma spp. I I + +
(G. insularis, G. rupestre)

Bark, leaves, stems, and flowers used medicinally in Melanesia and Polynesia

Nypa fruticans M,W I,R ++ ++

Fronds used for thatching, umbrellas, raincoats, coarse baskets, mats and bags; young leaves used for cigarette wrappers; leafstalks for fuel, arrows, and floor slats; young leaves when placed on sea reportedly attract fish in Papua New Guinea; young shoots used medicinally in PNG; sugary sap from young inflorescence edible and fermented into an alcoholic beverage or vinegar; young seeds edible; mature seeds used as buttons in PNG

<u>Pemphis acidula</u>	O,I,C,M	I	+++	+++

Ancestral tree of the people of Kabara and Wagava, Fiji who believe they originated as its fruit; referred to by the title of <u>Vu</u> (forefather) on Kabara, where only one tree remained in the 1930s; extremely hard wood favored for carved objects such as house frames, canoe parts, keels, connecting pegs, and paddles, digging sticks, clam knives, tool handles, thatching needles, pipes, back scratchers, fish hooks, fishnet frames, fishing poles, shuttles and meshing needles, fish, eel, and rat traps, spears, fish clubs, war clubs, darts, food containers, mortars and pestles, pounders, pump drill pieces, coconut huskers, combs, drums, tops, throwing sticks, and other toys, etc.; a preferred fuelwood with a very hot flame; wood used for spear of wave magician and as staff for magic dances in Ifaluk; old wood used to smoke skirts in Tuvalu; rotting wood mixed with coconut oil as a cosmetic; bark, leaves and flowers used medicinally in Tahiti and Micronesia; bark and leaves mixed with toddy as baby food in Ifaluk; fruits sometimes eaten in Kiribati; used as pigfeed in Tokelau; scraped bark yields a red dye in Tokelau

<u>Scaevola sericea</u> (<u>S</u>. <u>taccada</u>, <u>S</u>. <u>frutescens</u>)	O,I,C	I	+++	+++

Protected in garden areas in Kiribati and occasionally planted in houseyard gardens; associated with phases of the moon in Kiribati; features in legends and chants in Hawaii; wood sometimes used for roofing strips, rafters and supports and house decking, rafts, canoe paddles and poles, scoopnet handles, eel traps, reef markers, net gauges, shark rattles, throwing sticks and toy darts; hollow branches used as popguns or blow guns in games in Tuvalu, Tokelau, Kiribati and Nauru; pith of large trees cut into strips and made into paper-like garlands and headbands in Kiribati and Nauru and to caulk canoes in Tuvalu; pith chewed as gum in Kiribati; leaves made into tuna lures in Tokelau; leaves boiled with women's grass skirts in Kiribati to dye them brown and make them durable; bark, white heartwood, roots, leaves, fruit and seeds used medicinally; leaves used as a contraceptive in New Guinea; leaves used for wrapping penis in Vanuatu circumcision ceremony; leaves used to wrap food and to cover the earthen oven; leaves used as pigfeed in Tokelau; fruits used in magic in Kiribati; fruit used in fishing magic in Ulithi; leaves used for cleansing diving goggles in Polynesia, for shelter in fishtraps in Kiribati, to scent coconut oil in Micronesia, in head garlands and worn in ear slits in Tuvalu, and occasionally for compost or fertilizer; flowers used in garlands in Tuvalu, Kiribati and Nauru; fruit eaten by pigeons or fed to them as pets in Tokelau

<u>Sida fallax</u>	I,N,C	I,A?	+	++

Very important in Hawaiian mythology and believed to be one of the forms taken by the goddess of the hula, Laka, and a prostrate form the body of the god Kane 'Apua, the healer and god of taro planters and the brother of Pele, the fire and volcano goddess; flower of the island of Oahu, Hawaii and of Abemama, Kiribati; planted as an ornamental and commercial crop for the sale of its flowers and garlands in Hawaii and Kiribati; possibly the only plant deliberately cultivated for lei making in ancient Hawaii; stems tied in bundles to encircle swamp taro mounds, as connectives in house thatching, for rough baskets, and floor covering under mats in Hawaii; bright orange flowers very important for garlands in Hawaii, Kiribati and Nauru, formerly reserved for persons of high rank in Hawaii and Kiribati; flowers and tender meristem occasionally used to scent coconut oil in Nauru; flowers and leaves used medicinally; flowers used in magic, particularly love magic, in Kiribati; bushes important in the preparation of swamp taro beds in Hawaii and leaves and flowers dried to make the strongest fertilizer or mulch for giant swamp taro and other crops in Kiribati; sometimes used as fresh compost in Kiribati; several varieties recognized in Hawaii

<u>Sophora tomentosa</u>	O,I	I	+	+

Used medicinally in Melanesia and Tahiti; used to cure puncture wounds from poisonous marine animals

<u>Suriana maritima</u>	O	I	+	+

Hard wood used in general construction and for fishhooks, adz handles, spears, frames for lobster nets, canoe booms and connectives, and fuelwood; bark used medicinally in Ulithi

<u>Tephrosia purpurea</u> (<u>T. piscatoria</u>)	I,N	I,A	+	++

Possibly cultivated in the past in Samoa; extract of root used as a fish stupefacient throughout Polynesia and Melanesia; roots, young leaves and buds used medicinally in Fiji, Tahiti and Hawaii

<u>Wollastonia biflora</u> (<u>W. strigulosa</u>, <u>Wedelia biflora</u>)	O,I,P	I	++	++

Leaves, sap, fruits and roots used medicinally in Melanesia, Polynesia and Micronesia; young fruit eaten in Solomon Is. and leaves eaten in New

Caledonia; flowers used as a contraceptive in Solomon Islands; leaves used in compost or fertilizer in Kiribati and Namoluk; stems used for cordage in Melanesia; entire plant used in magic in Namoluk to protect canoes at sea from breaking up

Wikstroemia foetida (*W. elliptica*)	I,N,C	I,A	+	++

Occasionally planted in Hawaii; bark used in Melanesia and Polynesia as a source of fiber and cordage for fishing nets, etc; leaves, bark and root used medicinally in Melanesia and Polynesia;; bark root and leaves used as a fish poison in Tahiti and Hawaii; flowers and bright red fruit used in garlands in Hawaii

Ximenia americana	O,I	I	+	+

Hard wood used for making headrests in Fiji; fruit edible and a favored food of pigeons; stems and leaves used medicinally in Melanesia

TREES

Acacia simplex (A. simplicifolia)	O,I,M	I	++	++

Wood occasionally used in general construction, for handicrafts and tools, and for firewood; leaves used medicinally in New Caledonia and Tonga; leaves used as spoons in Fiji; seeds occasionally used for necklaces in Samoa

Aidia cochinchinensis (Randia cochinchinensis)	I,N	I	+	+

Wood used to make thatch rafters for houses and coconut huskers in Samoa and for canoe booms in Futuna; fruit eaten by children in Nauru

Avicennia marina (A. alba)	M	I	++	++

Wood used in general construction; bark used medicinally and sap of leaves on poisonous fish punctures in PNG; resin used as a contraceptive in PNG; fruits edible in PNG

Barringtonia asiatica	O,I,C	I	+++	++

Occasionally planted in houseyard gardens; occasionally planted from drift seeds in Kiribati; tree believed to be inhabited by ghosts in Tokelau; said used to assist priests (kahunas) in praying someone to death in Hawaii; wood used for general construction, handicrafts and occasionally for boatbuilding; used for firewood in Micronesia and for cooking coconut syrup in Nauru; bark, root, flowers, fruit and seeds used medicinally in New Guinea, Polynesia and Micronesia; seeds crushed to yield fish poison and insecticide; dried fruit used as fishnet and turtle net floats and for games in Fiji; leaves used to parcel food and line earthen oven; some parts (possibly the fiber from the fruit) used to make women's skirts in Fiji

Barringtonia racemosa	I,W	I	+	+

Used for light construction and house beams in Papua New Guinea; bark and leaves used medicinally in Melanesia

Bruguiera gymnorhiza (B. conjugata, B. eriopetala)	M	I,R	+++	+++

Wood used in construction, for tools, coconut huskers, bows, gunwales, masts and other canoe or raft parts, and highly valued for firewood and

charcoal making; bark a good source of tannin, bark and flowers yield dark brown dye used for bark cloth in Tonga and Fiji; red dye from bark used to preserve and color canoe sails in Kiribati; skin of fruit used to make black dye for skirts in Nauru; bright red flowers and white flowers strung in leis in Kiribati, Puluwat, Tonga and Hawaii; fruit (hanging radicle) used as food in Melanesia, an emergency food in parts of Polynesia and processed into a bread-like delicacy in Nauru; hollowed fruit use as a whistle in Samoa; fruits and bark used medicinally

<u>Calophyllum</u> <u>inophyllum</u> O,I,N,C I,A +++ +++

Occasionally planted in houseyard gardens; a sacred tree in the past on Tabiteuea in Kiribati; features in Hawaiian chants and considered a sacred tree and planted around the most sacred temples in parts of Polynesia; the name of one of the three islands of Tokelau, Nukufetau, means the village or place of <u>C</u>. <u>inophyllum</u>; associated with rituals of human sacrifice and cannibalism in Tahiti and planted in groves and individually in Hawaii; fruit used in fishing magic and wood for spears used by wave magicians in Ulithi; reportedly semi-domesticated and planted for shoreline protection in Solomon Islands; strong and durable wood used in house construction, for woodcarving, canoe hulls, bowpieces, mastheads, rudders, booms and connectives and other durable canoe parts, and a wide range of wooden objects such as kava bowls, horsecarts, cooking vessels, calabashes, food containers or boxes, bailers, ladles, hat blocks, water-tight fishing boxes, headrests/pillows, canoe paddles, spades, digging sticks and other tools, tool handles, stilts, fishing poles, weapons, drums and slit-gongs, diving goggles, pump drill pieces, coconut tree-climbing clasps/ratchets, etc.; stems used for scoopnet and birdnet frames; used for firewood; sap used for caulking canoe hulls in Vanuatu and Nauru; fruit latex used as glue in New Guinea; leathery leaves used to make small kites and worn in ear slits in Tuvalu; seeds, leaves, gum and bark used medicinally; seeds provide brown dye for tapa cloth in Samoa, Tahiti and Hawaii; skin and outer flesh of fruit eaten in Kiribati and Puluwat; oil from seed kernel burned to provide illumination (as lamps); fruit burned as mosquito repellant; seed kernel pressed to produce highly-valued greenish oil and used to scent coconut oil for royalty in Fiji and Tonga; soot from seed used a tatoo pigment in Ulithi; sap used to pull out facial hair in Ulith; seed used in necklaces and as marbles by children; green and mature seeds used to make hair tonic in Nauru; fragrant flowers used in garlands and to scent coconut oil in Polynesia and Micronesia

<u>Casuarina</u> <u>equisetifolia</u> O,I,N,P I,R +++ +++
(<u>C</u>. <u>litorea</u>)

Features in Fijian and Polynesian mythology and legends; the emblem tree of Oro, the god of war and planted around sacred areas (marae) in Tahiti; reportedly semi-domesticated in Solomon Islands; planted to stabilize coastal areas in land reclamation, as windbreaks, hedges, and living fences around homes and to protect coastal plantations and as a nitrogen-fixing tree; common ornamental or street tree; planted near

burial sites in Fiji; durable heavy wood used in construction and woodcarving and for war clubs, dart tips, bark cloth beaters and anvils, fans, digging sticks and other tools and tool handles, house posts, canoe hulls and parts, and other objects; excellent firewood; roots used to make fishhooks in Tahiti; bark and leaves used medicinally in Melanesia and Polynesia; bark provides a brown dye and tannin for tapa cloth in Tahiti

Cerbera manghas (C. odollam)	I,N,M,C	I	+	++

Occasionally planted as an ornamental; poisonous fruits and seeds used as a fish poison in Melanesia and Polynesia and reportedly for suicide in the Marquesas; wood used for general construction and handicrafts; trunks used for canoe hulls and hollowed into drums with sharkskin heads; bark and leaves used medicinally in Melanesia and Polynesia; flowers used in garlands and decoration; distinct red and green fruited forms or cultivars recognized in Vanuatu

Ceriops tagal	M	I	+	+

Very durable wood used in house construction in PNG; excellent firewood; excellent source of tannin; dye obtained from bark in PNG

Cocos nucifera	O,I,N,C	A,I?	+++	+++

The most useful of all plants in the Pacific; features in mythology, legends, songs, proverbs and riddles throughout the Pacific; of ceremonial importance and its leaves a sign of high rank in Polynesia and Micronesia; the tip of the frond a religious emblem in Tuvalu; planted in extensive monocultural plantations, as well a being the most important intercrop or agroforestry species in smallholder mixed cropping systems; specific trees or two trees planted together serving as boundary markers in Tuvalu; trunk used in house construction for poles, rafters, and beams and for woodcarving, in fencing and for animal pens, for other articles such as food containers, tools, spears and weapons, drums, canoe planking and small-canoe hulls and paddles, walking sticks, fish clubs, and, most recently, for sawn timber using portable timber mills; major source of fuel on most smaller islands, with almost all parts being used; coir and dry leaves important as tinder in making fire by friction and carrying fire; swelling at base of trunk made into food containers and large hula drums in Hawaii; bark used for scenting body oil and for smoking skirts; mature and young leaves used for weaving baskets, food containers and parcels, mats, housing thatch, tables or table mats for feasts, trays, fans, balls, weirs/barricades for communal fish drives, and other plaited ware; young leaves from germinating nut used to make a coconut-tree climbing bandage or foot-harness which is tied between the feet; unfurled immature leaves used to make skirts, body ornamentation, hats/eyeshades, baskets, fans and fishing lures; leaves used in magic, particularly garden magic and tied around trees in plantations as boundary markers or to ward off evil spirits and as a sign of no trespassing or tapu; old dried leaves and

husks used as mulching; midrib of leaflets or pinnules used in brooms, in weaving, toy windmills, for fishing lures and shrimp snares, to spear mudworms, small arrows, musical instruments, headdresses, combs, for stringing fish and oil-rich seed kernels burnt for illumination, fastening thatch segments, for strengthening bonito hooks, cooking skewers, toy canoes, and in a variety of other ways; woody leaf base and midribs of fronds used for house flooring and rafters, for sandals, carrying poles, toy boats, rattles, sledges or clappers, clubs or mallets, and to beat water during fish drives and for pounding and stabilizing banks of taro beds; doubled-over midribs of fronds used as cooking tongs; midribs of young fronds used for fishermen's belts in Tuvalu; burlap-like fibrous sheath at base of fronds used as tinder, toilet paper, gauze, a filter or strainer and to press medicine or coconut oil and to wrap bait for deepwater fishing and the earth ball on the roots of seedlings when transplanting; flower used in connection with religious ritual in Tahiti; kernel or endosperm of mature nut used raw, cooked and fermented in a variety of ways as a staple food, as a major food for chickens and pigs and ingredient in locally produced commercial livestock feeds, for fish and rat bait, and dried to provide the socially important scented and unscented coconut oil for soap, skin oil, cosmetics, perfume, and copra, the only export crop in many rural areas; chewed pieces of mature kernel used as popgun ammunition on Tuvalu; kernel of mature nuts hung in house rafters as emergency food for up to ten years; oil used as a preservative for tapa, carvings and other objects; soft flesh of immature nut an important weaning food and adult food; juice of immature nuts a nutritious local beverage, which is often sold, and considered a sacred offering to visitors in Kiribati and used in divination in Hawaii; oil chewed and spat on the ocean to calm the sea; sap from flower spathe used to make unfermented and fermented toddy and syrup, which are of considerable nutritional importance in Micronesia and on atolls; husk of some cultivars of green nuts eaten in atoll Polynesia and Micronesia; flower spathe sheath and dried fronds used to make torches for night fishing and for major nighttime ceremonial occasions; dried sheaths used as splints to set broken bones; flower spathe sheath and frond midribs used to splint broken bones in Tuvalu; coir of husk of both green and mature nuts used to make strong fibre and cordage (sinnet) for strainers, affixing tool handles, boat and house lashings, fishnets and lines, measuring tapes for garden lands, hammocks, belts, reef-walking sandals, canoe caulking, corks or stoppers, slings, toilet paper, baskets or carry bags, tying corpses for burial, and commercially to make brooms, brushes, fly whisks, doormats and other objects; green husks used to cover earthen oven; pieces of green husk used as temporary spoons to scoop meat out of green nuts; charred husk fibre used for black dye in Tokelau; shell of nut used to make cups, bailers, small bowls, cooking vessels, funnels, utensils, storage containers, fish hooks and lures, floats, knee drums, cymbals, lagging discs, toys and a wide range of handicrafts and high quality charcoal; roots used to make fish traps, floating cages, sand screens, and other objects; very important medicinal plant, with most parts used medicinally; leaning palms with excavated cavities or attached receptacles near the base used for water catchment; numerous named cultivars recognized in all parts of the Pacific, many of which have specialized uses, e.g., for drinking nuts, cup, or coir cordage

Cordia subcordata	O,I,C	I,A	++	+++

Planted as a ornamental shade tree in or near settlements; formerly many famous large groves in Hawaii; a favored shade tree in ancient Hawaii; features in Polynesian legends and chants, including the origin of fire from the underworld and, in Kiribati, is the totem of the Karongoa clan and features in mythology; soft but durable chocolate brown and blond wood used in general construction and among the most favored carving woods and used for making canoes hulls, thwarts, rudders, weather platforms, outrigger booms and paddles, furniture, headrests, bowls, trays, plates, combs, food stirrers, food containers or boxes, air-tight reef boxes for fishing equipment, fishnet floats, fishing rods, tools, coconut climbing sticks, toys, drums and slit-gongs, tobacco pipes, images of gods (tiki), and other carved objects for sale to tourists; young saplings used for fishing rods and flutes; inner bark used as pregnant women's girdle to provide magical powers in Kiribati and as sail ornamentation on Polynesian voyaging canoes; inner bark soaked in seawater made into dance skirts, hats, fans, baskets, garlands and, in former times, men's clothing; used for firewood and dry bark and wood used in making fire by friction; leaves, bark, growing tips and stems used medicinally; leaves used in arousing love in Kiribati and for love, wave and protective magic in Micronesia; leaves used to make brown dye in Tahiti and for pigfeed in Tokelau; brown dye made from roots in Tokelau; attractive orange flowers used in leis and garlands; seeds eaten, mainly by children, in Fiji, Tokelau, Puluwat and Ifaluk; seeds used to make paste for bark cloth in Samoa

Cycas circinalis (C. rumphii)	I,N,C	I,A?,R	+	++

Commonly planted ornamental; very important ceremonially in Vanuatu where its is planted in ceremonial dance grounds, pigs tethered to it before ceremonial feasts, leaves an important symbol of taboo or restriction, an emblem on the national flag, and its leaves put on belts by men to show rank of maturity or initiation, with burning leaves used to punish (burn) persons guilty of grave crimes; leaves used in Vanuatu to communicate messages, and leaflets of fronds to count people at feasts and to fix dates for marriages, important feasts, and important works by taking off successive leaflets until a given date; seeds edible after thorough washing and processing into flour; pith-like substance from trunk eaten in Guam and reserved as food for chiefs in the past in Fiji; an important famine or emergency food in the past; fruit, sap and pollen used medicinally in PNG; fronds used in decorations

Cynometra ramiflora (C. insularis, Maniltoa spp.)	M,C	I	+	+

Timber used in general construction and for houseposts; seed for children's games in Fiji; leaves used medicinally in Fiji

Diospyros spp. I,N I + +
(D. elliptica, D. ferrea, D. insularis, D. samoensis, D. vitiensis)

Timber valuable for general construction, handicrafts, and digging sticks and firewood; bark and leaves used medicinally in Melanesia, Tonga and Samoa; fruit of some species eaten

Dolichandrone spathacea M,I I + +

Wood used in general construction and for net floats; leaves used medicinally in Solomon Islands

Erythrina fusca M,W,I I + +

Leaves, bark and roots used medicinally in New Caledonia

Erythrina variegata var. orientalis (E. indica) O,I,N,C I,A ++ +++

Planted as one of the most common living fences and boundary markers; planted as shade, windbreaks, or green manure for coffee, cocoa and citrus plantations; common in houseyard gardens; flowering an important part of traditional agricultural calendar and the signal of the beginning of the yam planting season in many areas; the red flower a sign of blood and a declaration of war on Pentecost, Vanuatu; wood used in light construction, for small canoe hulls and outriggers, floats and for digging sticks; occasionally used as firewood; used for smoking bark cloth in Samoa to give it a deep brown color; leaves, flowers and bark used medicinally; seeds occasionally used in necklaces, by children as toys, and by heathen priests in Fiji to cover oracle boxes; flowers used in garlands in Samoa, Nauru and Puluwat; at least three distinct varieties or cultivars recognized in Vanuatu

Excoecaria agallocha M,O,W I ++ +

Timber used for general construction; leaves, bark, root and sap used medicinally; wood burnt to produce smoke as a cure for leprosy and to treat fish puncture wounds in Fiji; latex used to poison fish in PNG; leaves boiled with coconut sennit to make it black in Lau, Fiji

Ficus obliqua I,N I ++ ++

Wood used in general construction and for firewood; tree once regarded as sacred in Fiji and still regarded as sacred in Vanuatu; bast fiber used to make bark cloth in Fiji; roots, aerial roots, bark, and leaves used medicinally; leaves used in garlands and in ceremonial dress; fruit an important food of fruit bats, pigeons and other birds in Vanuatu

<u>Ficus prolixa</u> (<u>F. aoa</u>, <u>F. microcarpa</u>, <u>F. virens</u>)	I,N	I	++	+++

Tree regarded as having spiritual importance in many areas and the focus of creation mythology and cosmogony in Polynesia and Melanesia; important in rituals and ceremonies in Melanesia; is found in and serves as the focus for the ceremonial meeting place (<u>nakamal</u>) in Vanuatu; timber and aerial roots used in construction and tool making in Melanesia; occasionally used for canoe hulls in Papua New Guinea; large aerial roots used for canoe masts and hauling loads on Ulithi; occasionally used for firewood; bast fibre used to make bark cloth in Vanuatu, Fiji, Niue, and Tahiti, and for making very large seine nets in Tahiti; sap used as chewing gum and, in Vanuatu, for putty and caulking and to dye ceremonial sashes and belts; fruit cooked and mixed with coconut syrup in Nauru to make a pudding; sap used for chewing gum; roots, aerial roots, bark, fruit latex, and leaves used medicinally; leaves used in garlands and in ceremonial dress; latex used in waterproofing in Tahiti; fruit important food of birds and fruit bats

<u>Ficus scabra</u>	O,I,N	I,A?	+	+

Used for firewood; leaf used as a sandpaper substitute; roots, bark and leaves used medicinally in New Caledonia Tonga and Samoa; horses eat young leaves in Tonga

<u>Ficus storkii</u>	I,N	I	+	+

Leaves used as a green vegetable in Fiji

<u>Ficus tinctoria</u>	I,N,C	I,A?	++	+++

Widely cultivated and propagated vegetatively as a minor staple food plant in Micronesia and Tuvalu; wood sometimes used in light construction and for digging sticks, canoe connectives, fishnet frames, fishtrap parts, earth sieves and for firewood and making fire by friction; fibrous branches used to clean teeth; roots used in scoopnet frames in Kiribati, and ropes for fish drives in Puluwat; bast fiber used as cordage for lashing and fishnets in Samoa and Tokelau; bast fiber of roots used for fish lures on Ifaluk and for cordage and chewed to make fuses or tapers used in medical treatment in Tuvalu; ripe or green fruit processed or cooked in many ways to produce a minor staple and made into puddings and dried preserved food in Tuvalu and Micronesia; fruit formerly used to dye bark cloth, hats, mats, etc. in Fiji, Samoa, Tokelau, Tahiti, and Kiribati; roots used to produce red dye for pandanus in Kiribati; sap used to produce red dye for face in Tahiti; fruit used as ammunition for popguns in Tuvalu; yellow leaves used in body ornamentation in Tuvalu; young leaves and young inner bark used medicinally in Kiribati; leaves fed to pigs in Tokelau and Kiribati

Glochidion spp. (G. ramiflorum, G. concolor, G. littorale)	I,N,C	I	+	++

Wood used in general construction and for firewood; leaves and bark used medicinally throughout the Pacific

Grewia crenata	I,N	I	+	++

Wood used for general construction and for firewood; bast fiber used for cordage; bark and leaves used medicinally; leaves used to cover earthen oven in Lau, Fiji; ripening fruit a sign to harvest yams and taro in Vanuatu; seeds eaten in New Caledonia

Guettarda speciosa	O,I	I	++	+++

Occasional in houseyard gardens in Nauru; important in Kiribati and Tuvaluan legends and mythology; names of the leaf and the plant being associated with phases of the moon and stations of the sun in Kiribati; hard and durable wood used in construction, for pilings, fishtrap stakes, stakes to hold garden mulch in place, coconut huskers, fishing poles, floats, spears, thatching needles, fishing rods, fishnet and birdnet handles, stilts, eel traps, fruit harvesting sticks, bowls, slit-gongs, for canoe hulls, supports, steering paddles, bailers, poles for poling canoes, and floats; the most desired wood for tapa beating anvils in Tonga; wood used in games in Fiji; used for firewood and for making fire by friction; leaves used in fires for drying pandanus leaves and for toilet paper in Tokelau; dead wood used to smoke skirts in Tuvalu; bark, leaves, flowers and fruit used medicinally; leaf litter considered the most important component and source of black topsoil which is mixed with compost for the cultivation of giant swamp taro, pandanus and other crops in Kiribati; leaves, either alone or with other leaves provide one of the most important composts in Kiribati and Tuvalu; all pastes or preserves spread on Guettarda leaves for sun drying in Kiribati; leaves used to cover earthen oven and as disposable plates in Micronesia; leaves provide a jet-black hair dye in Kiribati; leaves used as a baby's washcloth in Ulithi; leaves used for pigfeed in Tokelau; leaves used in head garlands and worn in ear slits in Tuvalu; flowers used in garlands and for scenting coconut oil; flowers and young leaves soaked in water to provide deodorant and a women's love potion (love magic) or aphrodisiac in Kiribati to make their sweat fragrant; parts used as love charms in Ulithi

Gyrocarpus americanus	I,N	I	+	++

Timber used in general construction; bole used for canoe hulls in Vanuatu and occasionally for firewood; leaves and bark used medicinally in Tonga, Fiji and Vanuatu

Heritiera littoralis (H. ornithocephala)	O,I,M	I	+	+

Durable wood used in general construction, for canoes, wharves, and as firewood; stems, seeds and sap used medicinally in Melanesia; seeds eaten with fish in PNG

Hernandia sonora (H. nymphaeaefolia, H. ovigera, H. peltata)	O,I,C	I,A?	++	++

Possibly planted from drift seeds in Kiribati; bole used for canoe hulls, outriggers, freight-raft floats, fish floats, corks, paddles, bailers, bird-net handles, wooden pillows, cricket bats, rat traps, and in light construction; used occasionally for firewood; bark, stem, leaves, fruit and seeds used medicinally in Melanesia, Polynesia and Micronesia; leaves used to make black paint in Truk; leaves used as compost and worn in ear slits in Tuvalu and as pigfeed and in dancing skirts in Tokelau; hard dark brown seed used in necklaces and handicrafts and as marbles by children

Hibiscus tiliaceus	O,I,M,N,P	I,A	+++	+++

One of the most useful trees in the Pacific; commonly planted as living fencing and animal pens and in coastal areas, near houses, in gardens, and as an ornamental or shade tree; a creeping variety planted as windbreaks in Hawaii; its presence in forested areas considered a sign of former cultivation in Hawaii; features in eastern Polynesian legends and Hawaiian firemaking legends; commoners not allowed to cut branches without permission of chiefs in Hawaii; branches borne in battle by priests as a good omen and allowed to fall in retreat in Hawaii; born by attendants at presentation of first fruits to kings on Easter Is.; branches used as tapu markers to delimit restricted areas in Hawaii; used to make spears used in typhoon magic in Ulithi; soft wood used in light construction and woodcarving, for house rafters, pig tethering posts, for canoe outriggers, spreaders, bailers, booms and occasionally hulls, fishing rods, hoists and floats, fishnet frames and handles, bows, fruit-picking rods, tools and tattooing comb handles, kite struts, jackstraw sticks, pestles, breadfruit splitters, coconut huskers, net floats, spears, shoreline posts to delineate fishing zones, fishing gear containers, noddy bird net handles and frigate bird nesting platforms (Nauru), and other purposes; a decent firewood, especially for slow smoking; used in making fire by friction; wood dried for six months used for fireworks in Hawaii; bast fibre used as canoe caulking and to make cordage for clothing and dancing skirts, and kilts, coconut climbing bandages or foot-harnesses, mats, sandals, sewing tapa, bark cloth paint brushes, making fishnets, fishing line and lures, slings, kava strainers, sandals or thongs, tying corpses in tapa, and cordage for tying, lashing and binding canoes, housing and other things; bark used

to strain kava in Pohnpei to give it its preferred slimy consistency; leaves, terminal buds, unopened flowers and bark used medicinally, with leaves being used to reduce hemorrhaging and for treating neurological disorders; leaves used to parcel food, especially seafood, as plates, and to line and cover the earthen oven; leaves widely used as toilet paper; flowers used in garlands in Hawaii; bark, shoots, and sapwood eaten in New Caledonia and other parts of Melanesia; leaves occasionally added to compost in Kiribati and Tuvalu; a number of distinct varieties or cultivars recognized in Melanesia and Polynesia

Inocarpus fagifer (I. edulis, I. fagiferus)	M,W,N,C	I,A?	++	+++

Tree features in Polynesian mythology and is the sacred tree of the people of Moce, Fiji, who are referred to as Vuata Ivi (fruit of the ivi); to injure the tree in any way was taboo on Moce and the first fruits were offered to priests; traditional calendar associated with its fruiting in Lau, Fiji; commonly planted or protected as boundary markers; wood used in general construction and woodcarving, for tool handles, kava bowls, tapa beaters, weapons, packing boxes, etc.; used for firewood; bark a source of dye in Tahiti; leaves used for indicating the value of pigs for ceremonial presentation in Vanuatu; leaves, bark and stems used medicinally; ripe seed, which tastes like chestnut, eaten cooked as a seasonal staple and preserved in the past in Polynesia and Melanesia; cooked seeds sold locally; gum from fruit used for caulking canoes in Uvea

Intsia bijuga	I,N,M	I	+	++

Occasionally planted in villages in Fiji; one of most sacred trees in Fiji; durable attractive dark red-brown wood used in house construction and most desired for woodcarving for canoes and canoe masts, kava bowls, headrests, containers, tapa beaters, combs, warclubs and a variety of other articles of interisland trade between Samoa, Tonga and Fiji; used for firewood; roots and bark used medicinally in Melanesia; seeds used for dancing anklets in Samoa

Leucaena insularum (L. forsteri)	O	I	+	+

Timber used in handicrafts, for general construction, and for firewood

Lumnitzera littorea	M,I	I	++	++

Tree planted for coastal reclamation in Tonga; features in Kiribati legends and songs; timber, which is resistant to marine borers and seawater, used for wharves, fishing poles, fishhook shafts, fishtrap stakes, crabtrap and fishnet frames, fishnoose poles, bridges, canoe parts, and fish traps, and in general construction, for house parts, spears, stilts, sticks for stick games, slit-gong drumsticks, thatching needles; used for firewood; deadwood used for smoking skirts and in garlands in Tuvalu; used medicinally in Melanesia; bright red flowers used in garlands in Tonga, Tuvalu and Kiribati

Mammea odorata	I,M	I	+	++

Used in housebuilding magic and ceremonies in Ulithi; wood used in general construction and for making canoe parts and paddles, adz handles, clubs, barbed spears, arrow points, and wooden fans; various parts used medicinally in Micronesia; sap used as an orange-brown hair dye which was a major item of interisland trade in Fiji; fruit eaten in Ulithi; flowers and fruit used in garlands in Micronesia and fruit used to perfume hair on Ifaluk

Manilkara spp. (Manilkara dissecta)	I,N	I	+	+

Wood used in general construction and for firewood; flowers used in garlands in Tonga

Metroxylon spp. (M. amicarum, M. salomonense, M. vitiense)	W,N,C	I,A,R	++	++

Commonly cultivated in New Guinea and Solomon Islands and occasionally in Melanesia and Polynesia; leaves considered among the best thatch in Melanesia; pith of trunk processed into starch which is the main staple in some coastal and riparian areas of Melanesia; sago starch a major item of coastal trade networks in New Guinea; starch made into puddings and desserts in Melanesia, Rotuma and Samoa; meristem eaten in curries by Indians in Fiji; seeds of M. amicarum used in necklaces and handicrafts and for buttons in western Micronesia

Morinda citrifolia	I,N,P	I,A?	++	+++

Tree features in Hawaiian, Tahitian and Tongan mythology; commonly planted in houseyard gardens; planted around houses to dispel evil spirits in Nauru; wood used in light construction, for digging sticks, adz handles, canoe parts, canoe paddles, stilts, and for firewood; poles used as taboo markers on reefs in Namoluk; fruit formerly eaten, especially by older people, but now mostly as an emergency food in Polynesia, but more widely eaten in Micronesia, often with toddy or sugar; fruit cooked and mixed with coconut to make pudding in Nauru; ripe fruit eaten as a stimulant on long sea voyages and used in love and fishing magic in Kiribati; fruit said to be eaten in the Mortlock Is. as a male contraceptive; bark and roots provide red and yellow dyes, respectively; roots mixed with lime to make red hair dye in Tuvalu; roots, bark, leaves, terminal buds and fruit used medicinally; stipules used to treat scorpion fish puncture wounds in Pohnpei; leaves fed to children as a treatment for vitamin-A deficiency in Kiribati; leaves used in head garlands in Tuvalu; leaves used as compost in Tuvalu; leaves used to wrap breadfruit seeds for cooking in earthen oven in Namoluk; juice of fruit mixed with spring water and drunk with kava to counteract unpleasant effects

<u>Neisosperma</u> <u>oppositifolia</u> (<u>Ochrosia</u> <u>oppositifolia</u>)	O,I	I	++	++

Reportedly semi-domesticated in Solomon Islands; wood used for timber, houseposts, rafters and frames, tools, canoe paddles and rudders and other handicrafts; used as firewood; seeds and perhaps fibrous flesh of fruit eaten occasionally in past and as an emergency or snack food in Melanesia, Polynesia and Micronesia; leaves used to parcel fish and seafood; bark used medicinally in Micronesia; a number of cultivars or varieties recognized in Melanesia

<u>Pandanus</u> <u>tectorius</u> (<u>P</u>. <u>odoratissimus</u>, <u>P</u>. <u>pyriformis</u>)	O,I,N,W,P	I,A	+++	+++

One of Pacific`s must useful plants; features prominently in Melanesian, Polynesian and Micronesian creation mythology, cosmogony, proverbs, riddles, songs, chants, and sayings and a symbol of love and a nature spirit in Hawaii; many famous pandanus groves recognized in Hawaii, with the Kahala area of Honolulu, formerly known for its groves, named after the tree; people of Kiribati referred to as the "Pandanus People"; commonly planted in houseyard gardens and in monocultural and mixed stands in garden areas; trunk and prop or aerial roots used in house construction, and for ladders, digging sticks, headrests, rat traps, containers, canes, musical bows, and for fuelwood; roots used to make the <u>ukeke</u> musical instrument in Hawaii; chewed pieces of prop root used as popgun ammunition in Tuvalu and dried to make fuses or tapers used in medical treatment in Tuvalu; green wood used in smokeless fires to wilt pandanus for matmaking; dead wood used to smoke skirts in Tuvalu; treated leaves of selected varieties used to make mats, baskets, hats, fans, bracelets, pillows, canoe sails, toy boats, weather screens, balls, toys and other plaited ware and for cordage; leaves used for

compost, bandages, swabs, corks, cigarette wrappers, whistles and ornaments, and for caulking; most parts used medicinally; male flower used to scent coconut oil, to perfume tapa cloth, in garlands, as a love charm and aphrodisiac, and worn in ear slits in Tuvalu and to make fine mats by Hawaiians in the past; the fleshy drupes (keys) of fruit of many varieties or cultivars eaten ripe as a snack food or cooked and/or dried and processed in a variety of ways in to make coarse starch or flour, desiccated cakes and other staple substitutes in Micronesia and atoll areas, but considered an emergency food in most other areas of the Pacific; aerial root tips eaten on some atolls; stalk or receptacle upon which keys are attached fed to pigs in Tokelau; yellow to red immature drupes strung in leis or garlands; fibrous chewed or dried mature drupes (or after being chewed by hermit crabs) used as paint brushes for painting tapa, for fuel, and as fishing line floats or markers; stilt roots used to make fish net floats, red dye, and fibre from stilt roots for ceremonial skirts in Kiribati, jump ropes in Tokelau, and for stringing leis and straining kava in Hawaii; numerous cultivars or distinct species of pandanus exist, many of which are shrublike cultivars, and not P. tectorius, although some authorities believe that most of the tree-like and edible cultivars could be variants of P. tectorius

Phaleria disperma	I,N,C	I	+	++

Planted as an ornamental in houseyard gardens; wood used for digging sticks and firewood; leaves boiled with coconut sennit to dye it black in Lau, Fiji; bark and leaves used medicinally in Fiji, Tonga and Samoa; leaves and flowers used in garlands and for scenting oil

Pipturus argenteus (P. incana, P. albidus)	I,N	I	++	++

Features in legends of the Polynesia god Maui capturing the sun in Tahiti; important in magic, sorcery and ritual in Melanesia; wood used in house construction, for fishhooks, rollers for hauling, and firewood and for making tapa beaters in Hawaii; strong cordage obtained from bast fibre used for fishing lines and nets throughout the Pacific, and for making ceremonial mats in Samoa and for tying the navel of newborn babies in Tokelau in the past; made into tapa cloth in Tahiti and Hawaii; bark cloth paste made from bark sap; bark, roots and leaves used medicinally; leaves used in ceremonial dress and to parcel food and line earthen ovens in Melanesia and as imitation feathers on fishing lures on Puluwat; flowers used to scent coconut oil in Lau, Fiji; seeds eaten by pregnant women and newborn babies in Hawaii and by children in Tokelau; young leaves eaten after cooking in toddy and coconut milk on Ifaluk; bark fed to pigs on Namoluk; a number of different red and green-leaved varieties or cultivars recognized in Vanuatu

Pisonia grandis (P. alba)	O,I,C	I	++	++

The favorite nesting or rookery tree for sea birds, including the black noddy, a ceremonial delicacy in Nauru; reportedly a protected sacred grove on Onotoa in Kiribati; leaves considered godlike on Tongareva; occasionally planted as a living bath house to provide shade and privacy and as a living pig pen in Tonga; soft timber occasionally used for light construction, fence posts, outhouse flooring, canoes, canoe outriggers, floats and bailers; occasionally used for firewood and to make fire by friction; leaves edible and used to wrap food for cooking and eaten with fish in Vanuatu and with taro on Kapingamarangi atoll; leaves a common pigfeed in Polynesia and Micronesia; bark and leaves used medicinally in New Caledonia, Polynesia and Micronesia; planted recently in Kiribati in houseyard gardens and at the hospital for edible vitamin-rich leaves; leaves used as mulching and green manure in Micronesia and Tokelau; a sterile cultivar with edible leaves, P. alba, is the lettuce tree of Indonesia.

Pittosporum arborescens   I,N   I   +   +

Used for firewood; fruit used to poison fish; leaves and bark used medicinally in Tonga

Pouteria costata   I,N   I   +   +
(Planchonella costata, Pouteria obovata, P. sandwicensis)

Timber used in general construction and for tools, and handicrafts and bark cloth anvils and spearpoints in Samoa; fruit reportedly eaten in Lau, Fiji

Polyscias spp.   I,N   I   +   +
(P. multijuga, P. grandifolia, P. samoensis)

Used medicinally in Fiji

Pongamia pinnata   O,I,M,N   I   +   +

Timber used for general construction; leaves, bark and roots used medicinally in Melanesia; leaves used in sorcery in Vanuatu

Premna serratifolia   I,N,C   I   ++   +++
(P. obtusafolia, P. taitensis, P. gaudichaudii, P. integrifolia)

Commonly planted in Fiji as a living fencing; emblem of the god Avaro in Tahiti; a symbol of love, affection, beauty, goodness, pleasure and virtue in Ulithi; wood used in general construction, for canoe connectives in Ulithi, canoe nails in New Guinea and to make specialized large fish hooks in Kiribati; used as firewood and for making fire by friction in Micronesia; best firewood to cook pandanus in earthen oven in Nauru; straight saplings or branches used as fishing rods; leaves and roots used to perfume coconut oil in Tuvalu, Kiribati and Nauru; bark,

leaves and fruit used medicinally for a wide range of maladies throughout Melanesia, Polynesia, and Micronesia; leaves used in ceremonial dress in New Guinea and worn in ear slits in Tuvalu; leaves used to arouse love and a mixture of the bark, coconut milk and Sida fallax flowers used to banish fear in marriage and to promote true love in Kiribati; important in fishing, canoe making and housebuilding magic in Ulithi; flowers used in coconut oil for hair in Samoa; flowers used in garlands in Nauru and Puluwat; seeds eaten by children in Tuvalu; ripe fruit formerly eaten with yams and a food of pigeons and fruit bats in Vanuatu; root provides dye in Tuvalu

Rhizophora spp. M I +++ +++
(R. mucronata, R. stylosa, R. apiculata, R. mangle)

Wood and stilt roots used in general construction, for needles and awls, earrings, combs, rat traps, headrests, coconut huskers, canoe parts, digging sticks, throwing sticks for games, for threading coconut shells for shark rattles, and scoopnet frames, and for fishtrap stakes in Kiribati because of its resistance to salt water and shipworm; an excellent firewood and also used to make charcoal in Fiji; supple stilt roots once used for bows and arrows in Polynesia and Melanesia and house walling on Kosrae; bark an excellent source of tannin and yields black-brown dye for bark cloth in Fiji and Tonga and for fishing line and nets in Samoa; red dye obtained from roots in Kiribati; bark used in red hair dye and to paint or glaze pottery in Fiji and Polynesia; bark scraped to scent coconut oil in Kiribati; bark, leaves, and fruit used medicinally in Melanesia, Polynesia and Micronesia; fruit a supplementary food and used in body ornamentation in Tuvalu; caulking paste made in past from boiled fruits; hollow fruit used as whistles in Samoa

Santalum spp. I,N I + ++
(S. neo-calidonicaum, S. yasi, S. insulare)

Hawaii called "Sandalwood Country" by the Chinese; cultivated in houseyard gardens; features in legends and songs in Tonga and Fiji; heartwood a major export during the nineteenth century and still exported to a limited extent from Fiji, Tonga, and Vanuatu and used for woodcarving for the tourist industry; heartwood used to scent coconut oil of the finest of chiefly quality which is used to scent tapa cloth and to anoint corpses in royal funerals in Tonga and used in religious ritual in Tahiti, with powdered heartwood scattered over coffin in chiefly burials in Lau, Fiji; bark burned as incense and a mosquito repellent; used medicinally in New Caledonia, Tonga, and Tahiti

Serianthes spp. I,N I + +
(S. melanesica, S. kanehirae, S. nelsonii)

Wood used in general construction, for canoe hulls and boatbuilding, woodcarving and firewood

Sonneratia alba	M	I	+	+

Wood used in light construction; root used as corks and floats in PNG; leaves, fruit, and flowers used medicinally in Melanesia; leaves used in garlands in Kiribati; fruit edible

Soulamea amara	I?	I	+	+

Timber used in general construction and for canoe platforms and firewood in Micronesia; long sapling used for poling canoes; flowers, fruit and bark used medicinally in Melanesia and Micronesia; bark used in magic to stop rain in Truk; fruit eaten by pigeons and bats

Syzygium richii (Eugenia richii)	I,N	I	+	+

Wood used in general construction, especially for fence posts, handicrafts, and tool making; used as firewood; leaves, bark and fruit used medicinally in Melanesia and Tonga; fruit used in garlands in Tonga; fruit of some species edible and a food of fruit bats and birds

Terminalia catappa	O,I,N,C	I,A,R	+++	+++

Favorite tree of the ancestral goddess Nei Tituaabane in Kiribati; tree important in sorcery in Nauru; commonly cultivated as an ornamental shade and nut tree; timber used in general construction and for canoe hulls, paddles, kava bowls, tool handles, warclubs, walking sticks, slit-gongs and drums; used for firewood; bark and leaves occasionally used to make black dye for pandanus leaves in Fiji and Niue; bark of young stems used for cordage; leaves used for wrapping food for cooking in the earthen oven in Kiribati; roots, bark, young leaves and fruit used medicinally; mature seed kernel widely eaten; seeds preserved twice yearly in the Solomon Islands for storage; ripe fruit surrounding seeds occasionally eaten in Nauru and Puluwat; fruit eaten by fruit bats; desiccated pith of fruit used to rub corpses in Kiribati; necklaces made of fruit in Nauru; seeds occasionally made into oil in Samoa for mixing with coconut oil

Terminalia littoralis (T. samoensis)	O,I,C	I	+	+

Wood used in general construction; roots and leaves used medicinally in Fiji, Tonga and Kiribati; seeds eaten in Fiji and Kiribati; red fruit used in garlands in Kiribati

Thespesia populanea	O,I	I	++	+++

Believed to be the shadow and spirit medium of the god of prayer and chanting in Tahiti and Hawaii; planted in sacred places in Tahiti, surrounding the house of Kamehameha I of Hawaii, and along bunds between taro gardens in Tuvalu; occasionally cultivated as an ornamental shade tree; branches attached to masts of canoes in Tahiti as a token of peace; durable (especially under water) attractive wood highly esteemed for general construction and wood carving of calabashes, containers, pestles, kava bowls, paddles, drums, weapons, fishing poles and fishnet handles, and carved figures, spirit images, ceremonial thrones and handicrafts throughout Polynesia; used for canoe hulls and floats in Papua New Guinea; provides sticks for stick games in Nauru; branches held by priests when praying and leaves offered to gods as a substitute for kava in Tahiti; leaves used in making fire by friction; bark used for tannin and dye; bark, stems, leaves and green fruit used medicinally; young leaves edible; leaves provide black dye for pandanus in Tuvalu; inner bark used for cordage in Hawaii; fruit used for tops in E. Polynesia; flowers used in garlands in Kiribati; leaves occasionally used in compost in Kiribati

Tournefortia argentea O,I,C I +++ +++
(*Messerschmidia argentea*)

Tree features in Tuamotuan and Kiribati mythology; timber occasionally used in light construction, occasionally for canoe hulls, connective and other parts, and for tools, cooking equipment, bailers, backrests, ladles, slit-gongs, diving goggles, carved masks, and rat traps, and for woodcarving; a favored firewood and formerly used in making fire by friction in Kiribati; leaves reportedly eaten raw in "salads" by boat crews in Kiribati; important pig food in Tokelau and Micronesia; leaves, leafbuds, growing tips, roots, bark, stems and fruit used medicinally; tender leaves and meristem used to cure fish poisoning in Nauru; leaves used as a female deodorant in Kiribati, in ceremonial dress in New Guinea, and as fish bait and to stuff pigs for cooking in Tokelau; seeds shot though hollow branch tubes in children's games; leaves used in compost and fertilizers in Kiribati; branches at ground surface and immature flower stalk used in voyaging and love magic in Micronesia

Vavaea amicorum I,N I + +

Wood used for light construction and firewood; wood burned in houses for illumination in Lau, Fiji

Vitex spp. O,I,N,P I ++ ++
(*V. negundo*, *V. trifolia*)

Sometimes cultivated in houseyard gardens; *V. trifolia* widely planted as mosquito-repelling hedges and windbreaks on Majuro and Kwajalein in the Marshall Islands; wood used in light construction and for tools and axe handles in Melanesia; used for firewood; branches used for fishing rods in Nauru; leaves burnt as an insect/mosquito repellent; leaves, bark and

fruit used medicinally; leaves eaten with dried coconut and leaves and wood made into tea in Hawaii; flowers, fragrant leaves and growing tips used in garlands

Xylocarpus spp. (X. granatum, X. moluccensis)	M,I	I	+	++

Timber used in general construction and for firewood; bark and seeds used medicinally in Melanesia and Polynesia; dye obtained from the bark in PNG; fruit used as a ball by children

Sources: General (Merrill, 1943, 1945; Barrau, 1958, 1961; Massal and Barrau, 1956; Jardin, 1974; Whistler, 1980a; Sterly, 1970; Stemmermann, 1981; Haddon and Hornell, 1975); Papua New Guinea (Sterly, 1970; Paijmans, 1976; Powell, 1976; Percival and Wormersley, 1975; Holdsworth and Mahana, 1983); Solomon Islands (Maenu`u, 1979; Sterly, 1970; Yen, 1976, 1984; Whitmore, 1966); New Caledonia (Rageau, 1973; Jardin, 1974); Vanuatu (Gowers, 1976; Sterly, 1970); Fiji (Seemann, 1873; J.W. Parham, 1972; Smith, 1979, 1981, 1985, 1988; Thompson, 1940; Singh and Siwatibau, 1980; Weiner, 1984; Brownlie, 1977; Kirkpatrcik and Hassall, 1981); Tonga (Yuncker, 1959; Thaman, 1976; Weiner, 1971; Sykes, 1981); Samoa (Setchell, 1924; Hiroa, 1930; McCuddin, 1974; Uhe, 1974; Whistler, 1980b, 1983, 1984; B.E.V. Parham, 1972); Wallis and Futuna (St. John and Smith, 1971); Niue (Sykes, 1970); The Cook Islands (Wilder, 1931; Hiroa, 1932ab; Whistler, 1987a); Tuvalu (Hedley, 1896, 1897; Chambers, 1975; Woodroffe, 1985)); Tokelau (Parham, 1971; Whistler, 1988); French Polynesia (Oliver, 1974; Decker, 1971; Guerin, 1982; Petard, 1986; Sachet, 1983; Wilder, 1934); Pitcairn (St. John and Philipson, 1962); Hawaii (Handy et al., 1972; St. John, 1973; Neal, 1965; Krauss, 1978; Rock, 1974); Easter Island (Metraux, 1940); Kiribati (Polunin, 1979; Luomala, 1953; Catala, 1957; Grimble, 1933, 1934; Moul, 1957; Overy et al., 1982; Fosberg and Sachet, 1987); Nauru (Thaman et al., 1985); Micronesia (Kanehira, 1933; Lessa, 1977; Stemmermann, 1981; Fosberg et al., 1979, 1982; Fosberg and Sachet, 1984; Manner, 1987; Manner and Mallon, 1989; Wiens, 1962; Wester, 1985; Christophersen, 1927); Marshall Islands (Bryan, 1972; Fosberg and Sachet, 1975; Lamberson, 1982); Pohnpei (Lessa, 1977; St. John, 1948; Niering, 1956); Truk (Lessa, 1977; Marshall and Fosberg, 1985); Yap (Alkire, 1974); Palau (Fosberg et al., 1980); Guam and Marianas (Stone, 1970; Fosberg et al., 1975); and personal records and observations by the author and personal communication with F.R. Fosberg and W.A. Whistler.

ATOLL RESEARCH BULLETIN

NO. 362

SUBSTRATA SPECIFICITY AND EPISODIC CATASTROPHE: CONSTRAINTS ON THE INSULAR PLANT GEOGRAPHY OF SUWARROW ATOLL, NORTHERN COOK ISLANDS

BY

C.D. WOODROFFE AND D.R. STODDART

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

SUBSTRATE SPECIFICITY AND EPISODIC CATASTROPHE: CONSTRAINTS ON THE INSULAR PLANT BIOGEOGRAPHY OF SUWARROW ATOLL, NORTHERN COOK ISLANDS

BY

C. D. WOODROFFE [1] and D. R. STODDART [2]

Coral atolls are natural laboratories within which to examine ecological processes (Sachet, 1967; Lee, 1984). They are often isolated, in some cases little disturbed, and have a geologically recent history of terrestrial plant colonisation. Reef islands around the rim of most atolls are Holocene in age. They are composed of biogenic skeletal sediments and have developed since reef growth caught up with sea level which stabilised after post-glacial sea-level rise. Plant colonisation of most of these islands must have occurred over a period of no more than 6000 years.

Reef islands on coral atoll rims provide an opportunity to test premises and predictions of the MacArthur and Wilson theory of island biogeography (MacArthur and Wilson, 1967). This theory suggested that inter-archipelagic (between-atoll) and intra-archipelagic (within-atoll) variation in plant species richness relate to different processes. Inter-archipelagic trends in diversity reflect regional scale floristic patterns, largely a function of immigration rate which is dependent on distance from 'mainland' source. Intra-archipelagic diversity, on the other hand, reflects local scale differences in plant occurrences, which relate closely to island area, and are a response to area dependent extinction rate. MacArthur and Wilson postulated that the extinction rate would be high on small islands (MacArthur and Wilson, 1967).

Niering (1963), in a study of the vegetation of Kapingamarangi Atoll in the eastern Caroline Islands, demonstrated a relationship between the number of plant species on an island and the logarithm of island area (using 33 islands, 0.01 to 32.0 ha). On islands larger than 1.4 ha, the number of species increased linearly with log area, but on islands smaller than 1.4 ha, the number of species was relatively invariant with area. Niering interpreted this as a result of ecological control, with more mature soils, greater soil moisture and protection from salt spray on islands above this threshold size (Niering, 1963). Similarly Wiens (1962) suggested that the inflection in the species-area relationship resulted from freshwater lens development on islands larger than 1.4 ha.

Ecological control was indicated by Whitehead and Jones (1969) who demonstrated that the Kapingamarangi data could be more closely described by a curvilinear than by a linear correlation, and who divided the flora into strand, non-strand

---

[1]Department of Geography, University of Wollongong, Wollongong N.S.W. 2500, Australia

[2]Department of Geography, University of California, Berkeley, California 94720, U.S.A.

Manuscript received 10 September 1991

and introduced species. Only strand species were found on the smallest island, and as the pool of strand species was restricted the number on an island did not increase markedly as island size increased. The rapid increase in diversity on islands larger than 1.4 ha was attributed primarily to appearance of non-strand species on these islands, with introduced species appearing on the largest of reef islands (Whitehead and Jones, 1969).

MacArthur and Wilson (1967) used the Kapingamarangi data in support of their theory. However, they attributed the poor species-area relationship on small islands to episodic instability of those islands. They implied that catastrophic events, such as tidal waves or tropical cyclones, periodically totally devastate the smallest islands, and thus these are not maintained at equilibrium.

The species-area relationship found on Kapingamarangi is not replicated on other coral atolls for which there is comparable data. There is some evidence for an inflection in the species-area relationship with relatively invariant number of native species on islands smaller than 3 ha (79 islands, 0.04 to 178 ha) on neighbouring Ontong Java Atoll, in the Solomon Islands (Bayliss-Smith, 1973). On Aitutaki, an almost-atoll in the Cook Islands (15 islands, 1.0 to 71.3 ha), the species-area relationship is weaker than on Kapingamarangi, but a linear semi-log relationship does hold for herbs, and to a lesser extent for trees (Stoddart, 1975b). Aitutaki lagoon contains a volcanic island which may be considered a reservoir of potential plant colonists; the fact that these have not established on sandy reef islands demonstrates ecological selection of species which do colonise reef islands (Stoddart, 1975b). A strong linear relationship exists throughout a wide range of island sizes (20 islands, 0.01 to 138 ha) on Nui Atoll in Tuvalu (Woodroffe, 1986).

This paper examines the flora of Suwarrow Atoll, an isolated, uninhabited and largely undisturbed atoll in the northern Cook Islands.

METHODS AND AREA OF STUDY

Suwarrow Atoll (13°14'5, 163°05'W) is an isolated atoll in the northern Cook Islands (Figure 1). It is 272 km from the island of Nassau, 347 km from Manihiki Atoll and 460 km from Palmerston Atoll. The atoll is about 18 km from west to east, and 14 km from north to south. It consists of a lagoon, up to 80 m deep, studded with patch reefs. It is surrounded by a continuous atoll rim, breached only at one place on the northern side where there is an entrance to the lagoon. There are more than 40 reef islands on the atoll rim, the actual number recognised depending upon definition of individual islands. These islands range in area from 0.06 ha (Manu 4) to 41.6 ha (Turtle Island, only 18.3 ha vegetated). The sporadic vegetation cover on several islands has allowed further subdivision such that stands as small as 50 m^2 are considered islands. Whale Island has been subdivided into 15 smaller vegetated islands. New Island contains only 3 coconut trees and has the smallest vegetated area.

The atoll is influenced by southeasterly Trade winds, but lies in the hurricane belt and tropical cyclones come from the north or northwest. Severe storms hit the atoll in

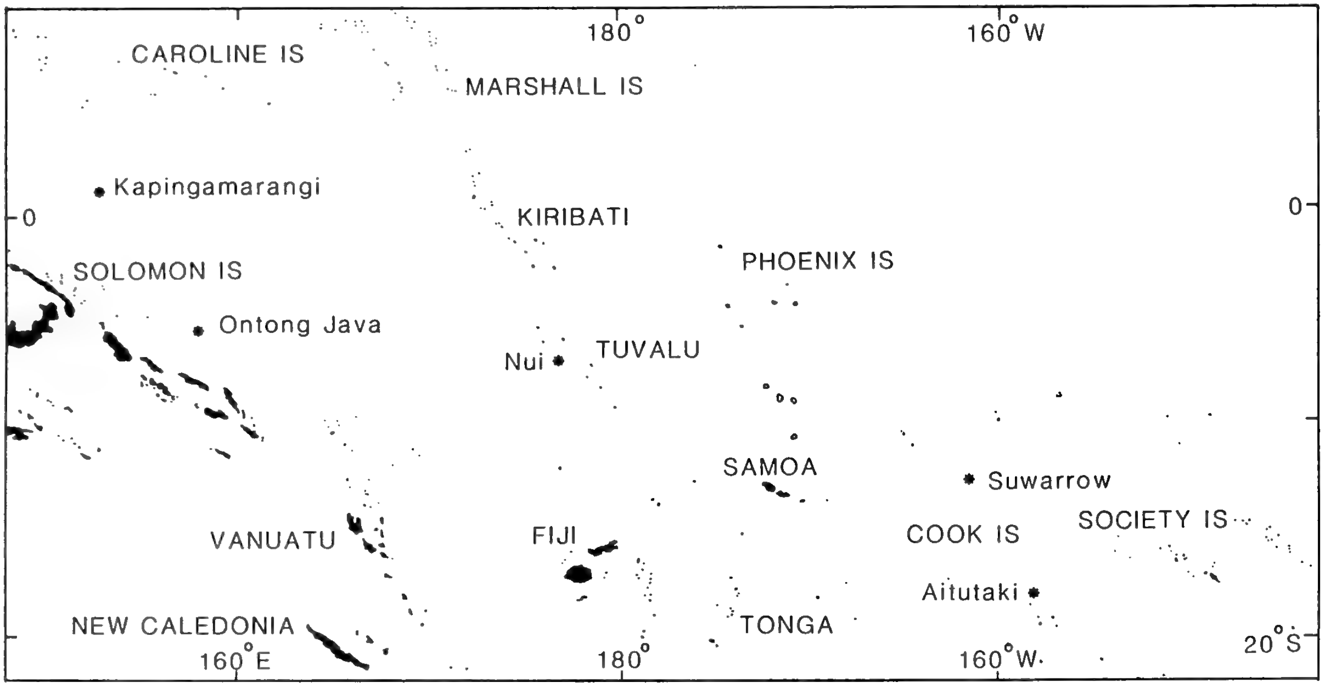


Figure 1. West and Central Pacific showing location of Suwarrow Atoll and other atolls mentioned in text.

1914, 1940, 1942 and 1967. Average annual precipitation is around 2400 mm. Tidal range is slightly less than 1 m.

Suwarrow is uninhabited; however it has had a history of sporadic settlement and some disturbance to vegetation. The atoll was visited by whalers, traders and pearlers. New Zealand coastwatchers lived there during World War II (Helm and Percival, 1973). For many years thereafter it had a lone inhabitant, Tom Neale, a New Zealander (Neale, 1968).

The fieldwork for this study was undertaken in September 1981. Each of the reef islands was visited and was mapped by pace and compass. All species growing on each of the islands were recorded, and an extensive collection was made, which has been deposited at the Smithsonian Institution. Sight and collection records are listed in Fosberg *et al.* (in prep.). The total flora consisted of 45 species of vascular plant, of which 22 species are introduced.

REEF ISLANDS OF SUWARROW ATOLL

The reef islands of Suwarrow Atoll are located at the lagoonward edge of the atoll rim, which varies from 100 to 800 m wide (Figure 2). Many of the islands are composed of a core of reefal limestone, with only a thin veneer of skeletal sands. Some of the larger islands, at the corners of the atoll rim, are unconsolidated boulder, shingle or sand islands.

Wood and Hay (1970) noted emergent reefal deposits at the northern end of Anchorage Island which they suggested might be Pleistocene in age. Radiometric dating implies, however, that all of the islands are mid to late Holocene in age (Kaplin, 1981, Scoffin et al., 1985). The exposed limestones of Suwarrow Atoll are described by Scoffin et al. (1985). There is a widespread *in situ* reef above the present level of coral growth and at about 50 cm above low water level. The reef surface which has been planed off partly by spalling contains numerous faviid corals in growth position, with specimens of *Acropora*, *Pocillopora* and *Millepora* to seaward. The raised reef forms the core of many of the smaller rocky islands. Radiocarbon ages of 4680±50 and 4650±60 years B.P. have been obtained on corals from this reef on Manu Island, an age of 4310±50 years B.P. on Whale Island, and 3670±50 years B.P. on a microatoll (possibly moated) at the northern end of Anchorage Island. It appears that the fossil reef was flourishing 4600-4300 years ago (Scoffin et al., 1985). On the southern rim of the atoll, however, a similar *in situ* reef is about 2000 years younger, radiocarbon-dated 2400±60 years B.P. at Entrance Island and 2400±60 years B.P. at New Island.

The second major limestone unit on the islands is a boulder conglomerate, containing boulders of massive and branching corals, cemented into deposits up to 2 m above the upper limit to coral growth. These boulder conglomerates occur to the oceanward of the *in situ* reef, though degraded remnants of reef do occur still further seaward (Scoffin et al., 1985). Radiocarbon dates on corals within these deposits range from 4460±50 to 2620±50 years B.P. The conglomerate was evidently deposited by storms. It is equivalent to the widespread conglomerate platform described by Stoddart

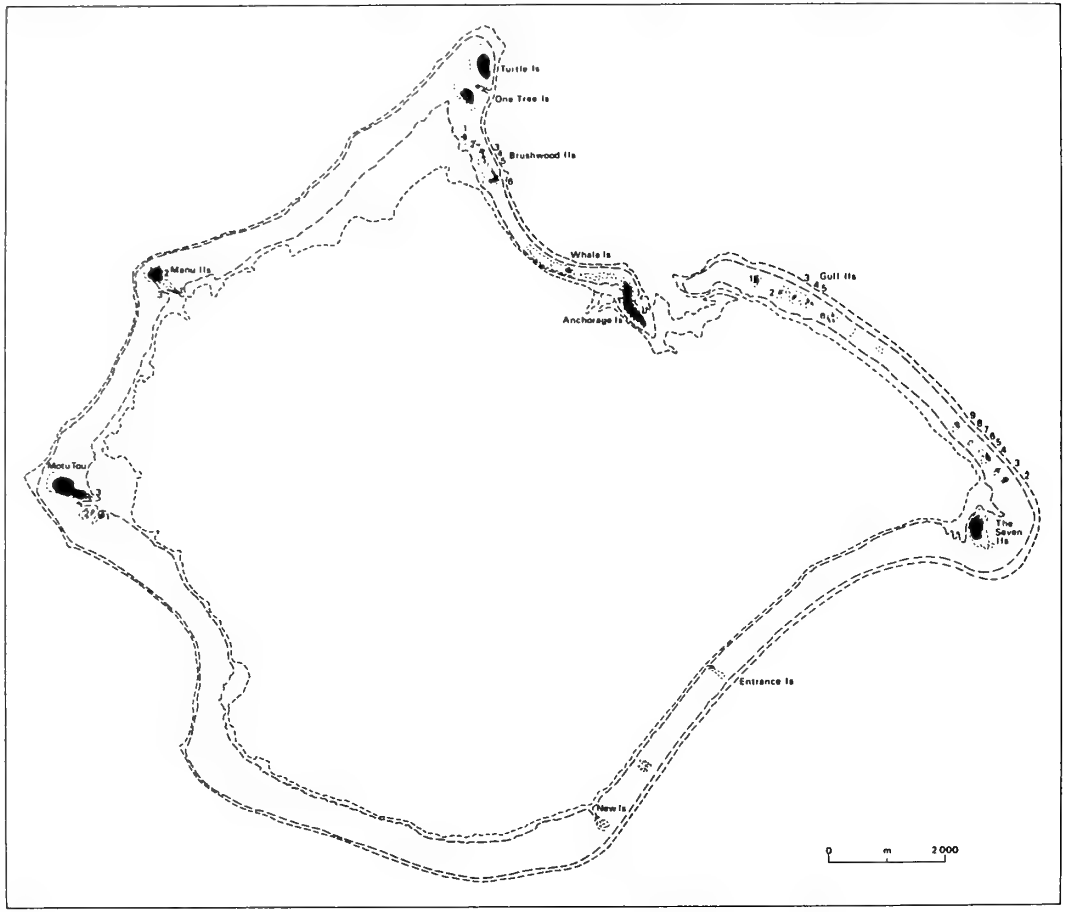


Figure 2. Suwarrow Atoll, and location of reef islands.

(1975a) on Aitutaki, and has been deposited during a series of episodes of storm activity over 2000 years of the late Holocene.

On the northeastern atoll rim, seaward of the Seven Islands there are 3 prominent fossil encrusting coralline algal ridges. The landwardmost ridge, about 1.5 m above low level water, in some places forms a part of the reef islands, and still contains traces of former groove and spur pattern. This ridge has been radiocarbon-dated 4220±60 years B.P. The intermediate ridge is degraded and has been radiocarbon-dated 3420±40 years B.P. The youngest, seawardmost ridge, only 50 cm above low water level and continuous with the present algal ridge, has been radiocarbon dated 1250±35 years B.P. The sequence of 3 ridges indicates periodic horizontal progradation of the reef during the late Holocene, and slight emergence of the mid-Holocene reef.

In addition to the cemented boulder conglomerate there are several unconsolidated boulder deposits. Much of the reef flat, particularly to the northwest of the atoll, is strewn with storm blocks, up to 4 m tall, and coral boulders. Kaplin (1981) reports a radiocarbon age of 3045±116 years B.P. on a boulder from a tract to the west of the westernmost island Motu Tou. Some of the reef islands are composed of unconsolidated boulder deposits, in particular Motu Tou, on which boulders have been radiocarbon-dated to 1225±175 years B.P. (Kaplin, 1981).

Other islands are made of moderately well sorted reef derived sands or coral shingle. The sands are dominated by benthic foraminifera, especially *Amphistegina lobifera* and *Marginopora vertebralis*, but abraded mollusc and coral fragments, *Halimeda* and the foraminiferan *Homotrema* are also prominent (Tudhope et al., 1985). Locally beachrock has formed, particularly on the oceanward beaches.

There is abundant evidence that storms have played a major role in the development and maintenance of the islands. Many of the deposits (ie boulder conglomerate, storm blocks) are storm derived. Wood and Hay (1970) believed that storms were instrumental in keeping the reef islands small. Kaplin (1981) also believed that islands remain small because sediments are washed away, but attributed this to tectonic sinking of the atoll. Tilting, rather than sinking of the atoll, was inferred by Scoffin et al. (1985).

VEGETATION AND FLORA OF SUWARROW ATOLL

The flora of Suwarrow Atoll is impoverished. Forty-five species of plant were collected or observed on the atoll, and 22 of these are considered introduced (Fosberg et al. in prep.). Several species which might be expected do not occur on the atoll, e.g. *Timonius polygama*, *Euphorbia chamissonis*, *Ipomoea pes-caprae*, *Sesuvium portulacastrum*. The native plants and their occurrence are listed in Table 1.

The only extensive vegetation on the rocky island surfaces, over i*n situ* reef, or boulder conglomerate is a scrub of *Pemphis acidula* (Plate 3). This often forms a wind-sheared fringe to the north of reef islands, from low divaricating shrubs 1-3 m high on the exposed northern side, to a thicket up to 7 m tall. *Pemphis* scrub is monospecific over

Plate 1. Motu Tou 1, coconut woodland and mixed scrub types. The island has a shingle substrate and is surrounded by boulder tract (foreground).

much of the islands but locally there is a ground cover of *Portulaca johnii*, *Boerhavia tetrandra*, *Lepturus repens* or *Fimbristylis cymosa*.

Where coral shingle or sand has accumulated there is often a scrub of *Tournefortia argentea* (Plate 2). This species commonly forms inliers within *Pemphis* scrub. It forms more extensive stands over some sandy or shingle islands (such as Seven 1 and Manu 1), where it is well-spaced and up to 6 m tall. In addition to the species which form a ground cover beneath *Pemphis*, *Laportea ruderalis* and *Lepidium bidentatum* are also found.

Scrub composed of *Scaevola taccada* var. *tuamotuensis*, which is a dominant vegetation type of Pacific atolls, is relatively restricted on Suwarrow Atoll. It forms a fringe around the outside of the larger sand islands, and on southeastern Anchorage Island forms a scrub 2 m tall, up to 17 m wide. *Suriana maritima* has a very patchy distribution on the reef islands of Suwarrow Atoll, and does not form the marginal scrub that it does on Aitutaki (Stoddart, 1975a).

Plate 2. Pemphis scrub with stands of *Tournefortia argentea* on sandy substrate, overlying *in situ* emergent reef (foreground), one of the Seven Islands.

Plate 3. Dense *Pemphis* scrub over rocky substrate, one of the Brushwood Islands.

The interior of three of the four largest islands (Motu Tou, Turtle and Anchorage Islands) is dominated by coconut woodland, up to 20 m tall. Beneath this woodland is undergrowth of *Scaevola* and *Lepturus*, often with *Triumfetta procumbens* and the fern *Polypodium scolopendria*.

Other woodland types are localised in comparison. Woodland of *Pandanus tectorius*, up to 18 m tall, is found on Motu Tou, Turtle and Anchorage Islands, generally with the ferns *Polypodium* and *Asplenium nidus*. Woodland of *Guettarda speciosa*, up to 16 m tall, is associated with *Pandanus* and coconut woodland on Motu Tou. Further open broad-leaved woodland occurs on Turtle, Motu Tou, Motu Tou 1 and Anchorage Islands (Plate 1); in some places this is dominated by *Pisonia grandis* and in others by *Cordia subcordata*.

An isolated storm block on the northwestern atoll rim was found to have 4 species on it: *Pemphis acidula*, *Digitaria stenotaphroides*, *Portulaca johnii* and *Laportea ruderalis*.

SPECIES-AREA RELATIONSHIPS

Many of the Suwarrow reef islands have been little disturbed by man. The only island to have been sporadically settled is Anchorage Island and it is on this island that introduced species are widespread. Many of these introduced plants are crop plants (*Musa*, *Carica* etc.) or ornamentals (e.g. *Hibiscus* sp.). Others considered introduced include large trees such as *Barringtonia asiatica* and *Calophyllum inophyllum* native to many Pacific Islands, but only found around a garden area on Anchorage. The polynesian rat occurs on Anchorage Island and does not appear to have spread to other islands. Conversely, four plants were found on other reef islands, but not on Anchorage (*Asplenium nidus*, *Digitaria stenotaphroides*, *Canavalia cathartica* and *Laportea ruderalis*).

In the analyses that follow introduced species have been excluded, and the 23 plant species considered native (including aboriginal introductions) are examined (Table 1). Figure 3 shows the relationship between the number of native species and log total island area, and between the number of native species and log total vegetated area. The relationship between species number and total area is weak ($r^2 = 0.57$); the relationship to total vegetated area is only a little stronger ($r^2 = 0.60$).

Figure 4 demonstrates species-area relationships for trees, shrubs and herbs. There is some ambiguity as to whether to classify individual plants, as a shrub or a tree; *Morinda citrifolia* and *Hibiscus tiliaceus* have been classed as trees and *Tournefortia argentea* as a shrub (Table 1) because that is the form they most frequently adopt on Suwarrow. The relationship between the number of species adopting each life form and log total area of the island is not strong; trees $r^2 = 0.31$, shrubs $r^2 = 0.54$, herbs $r^2 = 0.62$ (Figure 4). The relationship of trees, shrubs and herbs to log vegetated area is only a little stronger; trees $r^2 = 0.32$, shrubs $r^2 = 0.64$ and herbs $r^2 = 0.64$ (Figure 4).

The tree species-area relationship comprises two groups of islands. On the one hand there are the *Pemphis*-dominated islands covering a rocky substrate on which tree diversity is very low or from which trees are absent. On the other hand there are the sand or shingle cays, generally the larger islands on which woodland is established and which are relatively diverse in terms of tree species. Shrub diversity shows some relationship to island area, particularly to vegetated area, but the pool consists of only 4 species all of which are present on the largest islands. The extensive monospecific stands of shrubs that form (except *Suriana* which does not cover a large area on Suwarrow) further compounds the relationship. Herb species show the strongest relationship to island area; in part this may be a derivative of the association of herbs with trees. Locally herb diversity increases where there has been disturbance.

The differentiation between rocky islands dominated by *Pemphis* and sand and shingle cays is an appropriate one not only in terms of the distribution of tree species, but also in relation to the broader distribution of plants on the atoll. The rocky substrate, composed of boulder conglomerate, often with some adjacent *in situ* reef surface, represents an inhospitable environment, lacking soil or water, unfavourable for plant colonisation. There are only few species, principally *Pemphis acidula*, which can overcome these constraints of physiological drought. The area of these islands is determined principally by the topography of the emergent limestones. One Tree and Manu 2 (26.1 and 10.1 ha respectively) are relatively large islands, but because of their domination by rocky substrate, there are few or no additional species which can be expected to colonise and they are scarcely richer than much smaller adjacent islands.

Sand and shingle islands on the other hand are more diverse. However, these represent too small a sample to determine whether or not a species-area relationship exists, particularly in view of the differences in substrate (ie Motu Tou composed mainly of boulders and Seven 1 composed almost entirely of sand) and disturbance (widespread on Anchorage, restricted on Turtle and Motu Tou) between islands.

DISCUSSION

The species-area relationships for Suwarrow Atoll (Figures 3 and 4) are weaker and show more scatter than those for other Pacific atolls for two reasons. Firstly, many of the plants found on Suwarrow are substrate-specific, and there is an extremely limited pool of species which can colonise the rocky limestone surfaces, resulting in extensive monospecific stands of *Pemphis*. Secondly the atoll has been subject to episodic catastrophic hurricanes which devastate the small islands, probably remove much of the accumulated sediment and soil, and help maintain the islands at disequilibrium.

The importance of substrate characteristics has been realised in many island biogeographic studies as a factor influencing the diversity of habitats on islands. Buckley (1982) proposed a habitat unit model in which species-area relationships should be determined for various floristic elements in individual habitats or combinations of habitats, and summed to give a predicted species diversity for particular island areas. Substrate was shown to be a major component of habitat diversity on a group of islands off the coast of Western Australia (Buckley, 1982), but was less important on habitat islands on bare hypersaline mudflats in Queensland (Buckley, 1985).

Table 1: **Native species and their occurrence on the reef islands of Suwarrow Atoll**

Islands

Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
TREES																																																									
Pandanus tectorius	X									X										X		X	X	X				X		X																											
Cocos nucifera	X						X	X	X	X	X	X					X			X	X	X	X	X				X		X	X				X											X											
Pisonia grandis	X		X							X										X		X	X					X		X																X											
Hibiscus tiliaceus																								X						X																											
Cordia subcordata										X										X	X	X	X	X						X																											
Guettarda speciosa										X										X		X	X					X		X																											
Morinda citrifolia	X									X										X			X	X				X		X																											
SHRUBS																																																									
Suriana maritima																							X					X	X	X																			X								
Pemphis acidula		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X
Tournefortia argentea	X	X	X	X	X		X	X	X	X		X	X		X	X		X		X	X	X	X	X	X			X	X	X	X															X	X	X	X	X	X	X			X		X
Scaevola taccada	X	X							X	X										X		X	X					X	X	X																X								X			X
HERBS																																																									
Asplenium nidus																				X			X					X																													
Polypodium scolopendria										X										X	X	X	X					X		X																											
Digitaria stenotaphroides																			X																																						
Lepturus repens	X	X	X	X	X		X	X	X	X		X	X		X	X		X		X	X		X	X	X	X		X	X	X	X															X				X					X		X
Fimbristylis cymosa																X														X																											
Boerhavia tetrandra	X	X	X		X			X	X	X					X	X		X		X	X		X	X				X		X																X						X			X		X
Portulaca johnii	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X						X	X		X	X	X	X															X				X	X	X			X		X
Lepidium bidentatum	X																			X			X						X	X																											
Canavalia cathartica																						X	X																																		
Laportea ruderalis	X									X									X		X		X					X	X																												
Triumfetta procumbens								X															X							X																											
Ipomoea macrantha																														X																											

Key to Island Numbers: 1 = Seven 1, 2 = Seven 2, 3 = Seven 3, 4 = Seven 4, 5 = Seven 5, 6 = Seven 6, 7 = Seven 7, 8 = Seven 8, 9 = Seven 9, 10 = Entrance, 11 = New, 12 = Gull 1, 13 = Gull 2A, 14 = Gull 2B, 15 = Gull 3, 16 = Gull 4A, 17 = Gull 4B, 18 = Gull 5, 19 = Storm Block, 20 = Motu Tou 1, 21 = Motu Tou 2, 22 = Motu Tou 3, 23 = Motu Tou, 24 = Manu 1, 25 = Manu 2, 26 = Manu 3, 27 = Manu 4, 28 = Turtle, 29 = One Tree, 30 = Anchorage, 31 = Whale 1, 32 = Whale 2, 33 = Whale 3, 34 = Whale 4, 35 = Whale 5, 36 = Whale 6, 37 = Whale 7, 38 = Whale 8, 39 = Whale 9, 40 = Whale 10, 41 = Whale 11, 42 = Whale 12, 43 = Whale 13, 44 = Whale 14, 45 = Whale 15, 46 = Brushwood Main, 47 = Brushwood 1A, 48 = Brushwood 1B, 49 = Brushwood 1C, 50 = Brushwood 1D, 51 = Brushwood 2A, 52 = Brushwood 2B, 53 = Brushwood 3, 54 = Brushwood 4, 55 = Brushwood 5A, 56 = Brushwood 5B, 57 = Brushwood 6

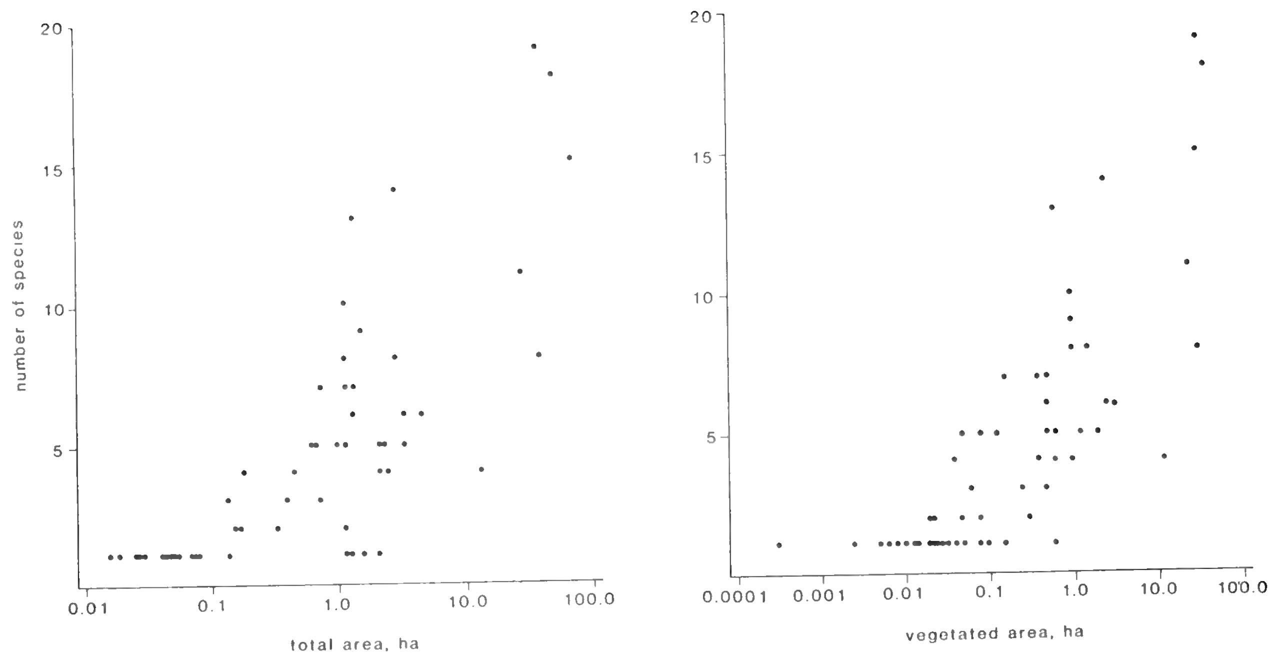


Figure 3. Species-area relationship (native species against total area, and native species against vegetated area).

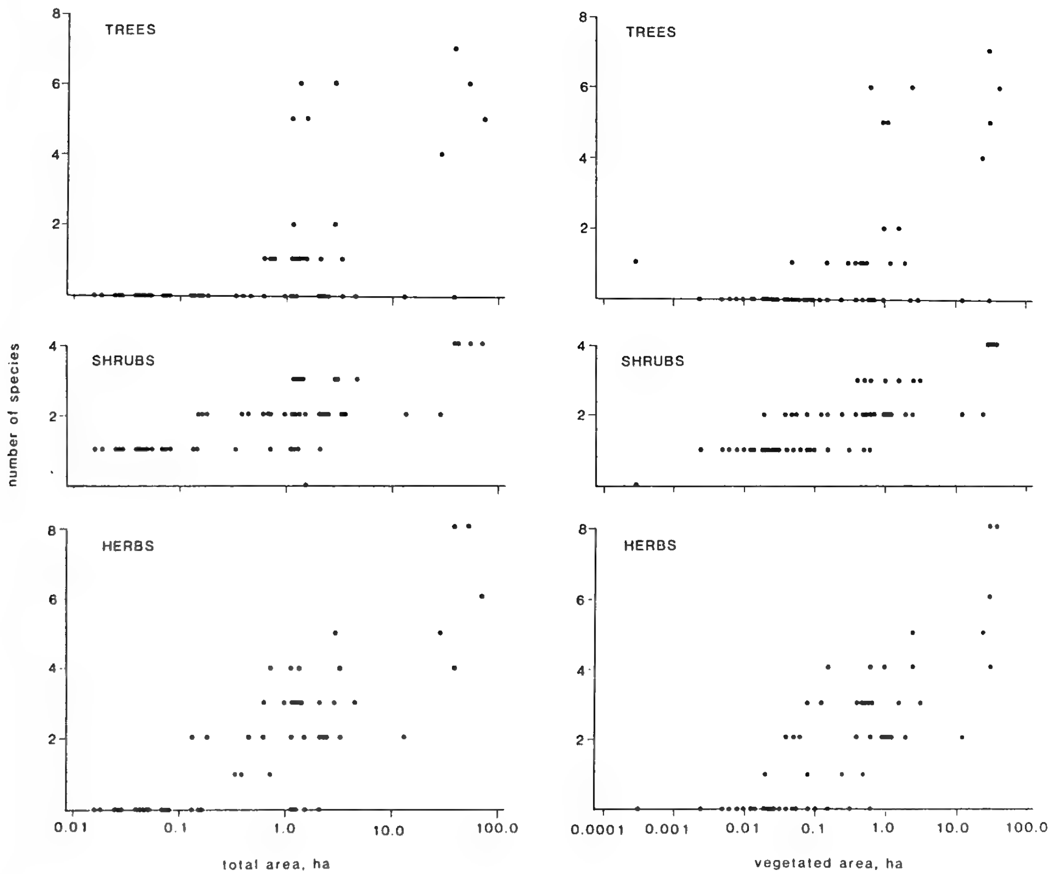


Figure 4. Species-area relationship (native species) for trees, shrubs and herbs against total area and vegetated area.

It is not possible to apply Buckley's habitat unit model to reef islands on Suwarrow Atoll. Firstly despite detailed mapping of vegetation types, the extent of sand or shingle sheets within the interior of *Pemphis* islands cannot be assessed. Secondly the floristic elements for rocky and shingle substrates would be so small as to be invariant with area of habitats.

The significance of catastrophic storms on coral islands has received considerable attention (Stoddart, 1962, 1963; Connell, 1978). On Suwarrow the importance of storms in generating storm blocks and rubble deposits, both with a high preservation potential, has already been noted. In addition, Wood and Hay (1970) have proposed that hurricanes have been instrumental in maintaining the small size of reef islands on the Suwarrow Atoll rim.

The impact of a severe storm on Suwarrow reef islands has been vividly described by Frisbie who, with his children, survived a severe hurricane which passed directly over the atoll in 1942 (Frisbie, 1944). After the storm Frisbie records that Anchorage Island was reduced to 3 barren cays and Whale, Brushwood, One Tree, all of the Gull group and 6 of the 7 Seven Islands had been completely washed off the reef flat (Frisbie, 1944 p. 225-6). Notwithstanding an element of exaggeration this is an impressive account of the destructive potential of catastrophic storms.

The small islands on the atoll rim of Suwarrow are subject to this periodic devastation, which is likely to maintain them at disequilibrium (Bayliss-Smith, 1988). On other reefs, small islands have been shown to have higher extinction rates, and consequently higher turnover rates of species than larger islands (Heatwole and Levins, 1973; Stoddart and Fosberg, 1982; Flood and Heatwole, 1986). The more stable the island the lower the turnover rate (Flood and Heatwole, 1986). Furthermore, on small islands the rate of geomorphological change and change of island area might be of a similar order to the rate of immigration, not permitting the island to attain species equilibrium (Buckley, 1981). These factors, however, are largely inappropriate on Suwarrow Atoll because the pool of species is constrained primarily by ecological potential.

Suwarrow Atoll lies on a steep floristic gradient across the Pacific Ocean. To the west are the floristically relatively diverse coral islands of Tonga, Tuvalu and Kiribati, and to the east the relatively impoverished islands of the Tuamotus and Society Islands. This florisitic gradient partly reflects the rainfall pattern across the Pacific from the wetter islands in the west to the drier ones in the east (Stoddart 1992). Nevertheless Suwarrow Atoll is floristically depauperate, because of its relatively isolated location, with absence of several species which might be expected. In comparing species-area relationships from west to east across the Pacific, this impoverishment to the east corresponds with a decline in the slope of the line of best fit and results in fewer species on islands of any specified size from Kapingamarangi to Aitutaki (Figure 5, Table 2). However, on Suwarrow Atoll the species-area relationship is particularly weak and shows great scatter because of the immaturity and ecological unfavourability of the reef islands (Table 2). By contrast, Nui Atoll, on which hurricanes are particularly rare, shows a strong species-area relationship because reef islands have relatively homogeneous and stable sandy substrates (Woodroffe, 1986). The reef islands of Ontong Java, Kapingamarangi and Aitutaki are more mature and more stable than those of Suwarrow. Of the atolls

Table 2: Details of Pacific atolls and their native plant species-area relationships (see Figure 5)

Atoll	Location	Distance to nearest island (km)	Approx. annual precipitation (mm)	Total land area (ha)	Total plant species	Total [1] native species	Smallest island (ha)	Largest island (ha)	Number of islands	Linear regression native species against log area		
										intercept	slope	r^2
Ontong Java	5°20'S 159°30'E	70	3000	650	146	82	0.04	178	79+	16.44	11.24	0.77
Kapingamarangi	1°05'N 154°45'E	300	2000	112	99	50	0.01	32	33	14.27	10.39	0.76
Nui	7°12'S 177°10'E	130	3000	337	86	44	0.01	138	20	19.90	7.47	0.94
Aitutaki	18°52'S 159°46'W	80	2000	244*	66*	42*	1.0	71.3	15	11.82	7.93	0.51
Suwarrow	13°14'S 163°05'W	270	2400	200	45	23	0.06	41.6	55	5.36	4.20	0.56

[1] including aboriginal introductions
* excludes volcanic islands
+ for which data available (Bayliss-Smith, 1973)

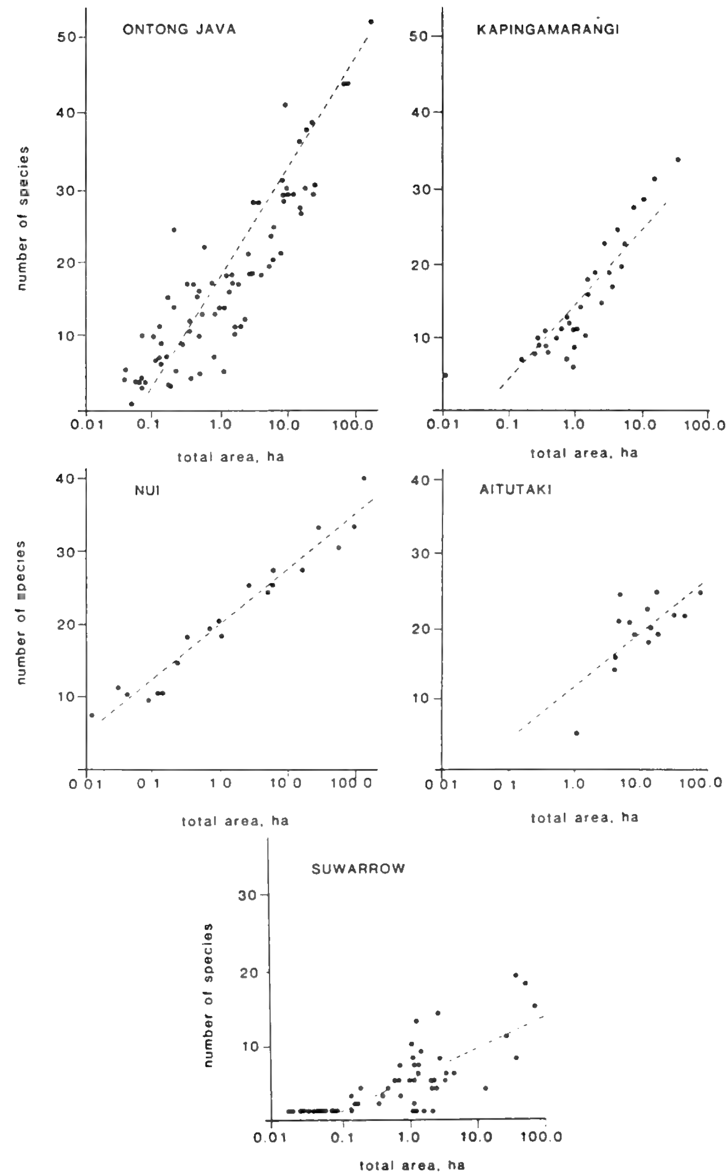


Figure 5. Species-area relationships for native species from Ontong Java Atoll (after Bayliss-Smith, 1973), Kapingamarangi Atoll (after Niering, 1963), Nui Atoll (after Woodroffe, 1986), Aitutaki almost-atoll (after Stoddart, 1975a) and Suwarrow Atoll. Dashed line shows least squares linear regression (details in Table 2).

examined in Table 2 Ontong Java is the closest to a mainland source area; Kapingamarangi and Suwarrow are the most isolated. The small island effect was attributed to ecological control by Niering (1963), Wiens (1962) and Whitehead and Jones (1969), but was attributed to episodic devastation by MacArthur and Wilson (1967), and it was considered that it operated up to a particular threshold size. On Suwarrow Atoll the species-area relationship is very weak, but this relates to a fundamental substrate constraint on many of the islands. The atoll demonstrates both the importance of ecological factors and episodic catastrophic storms in limiting species diversity on reef islands, but not in the way envisaged for atolls in the western Pacific. Catastrophic storms devastate reef islands, stripping many of them bare of vegetation and unconsolidated sediments. This ensures that these islands are composed largely of substrate unfavourable for colonisation by most plant species, and so limits diversity by way of the substrate-specificity of plants. Only on the large shingle and sand motus do woodland types develop and persist through storms, or recover after them, and islands which are more comparable in substrate terms with atolls outside or on the fringe of the hurricane belt develop. On these species-area relationships may be stronger.

CONCLUSIONS

Many of the smaller reef islands on Suwarrow Atoll are located on topographically high points on the atoll rim, which represent remnants of an emergent mid-Holocene reef with a conglomerate of coral boulders deposited between 4400-2600 years B.P. These islands generally contain very localised unconsolidated sediments, they are probably periodically stripped clean by catastrophic storms. The dominant vegetation is a scrub composed of *Pemphis acidula*. The unfavourable substrate, together with episodic devastation by storms means that islands of this type vary considerably in size, but are colonised by only a small pool of species and show a very weak species-area relationship. Larger boulder, shingle and sand islands have developed at the corners of the atoll and support woodland with a more diverse assemblage of species. The woodland has persisted through some storms, and has probably recovered after others. The Suwarrow flora is impoverished, due both to the distance from the Indo-West Pacific source region and to its isolation. Nevertheless it is the substrate specificity of the plants which are found there and the episodic catastrophic storms which account for Suwarrow Atoll having a considerably weaker native plant species-area relationship than other atolls in the Pacific for which comparable data are available.

ACKNOWLEDGMENTS

The work on Suwarrow Atoll was carried out as part of an expedition to the Northern Cooks organized by the New Zealand Oceanographic Institute, with financial support from the Royal Society of London and the Australian National University. Preliminary results on the subject of this paper were presented at the 15th Pacific Science Congress, Auckland, New Zealand (Stoddart et al. 1983).

REFERENCES

Bayliss-Smith, T.P. 1973. Ecosystem and economic system of Ontong Java atoll, Solomon Islands. Unpubl. PhD thesis, University of Cambridge.

Bayliss-Smith T.P. 1988. The role of hurricanes in the development of reef islands, Ontong Java Atoll, Solomon Islands. *Geographical Journal* 154: 377-391.

Buckley, R.C. 1981. Scale dependent equilibrium on highly heterogeneous islands: plant geography of the northern Great Barrier Reef sand cays and shingle islets. *Australian Journal of Ecology* 6: 143-147.

——— 1982. The habitat unit model of island biogeography. *Journal of Biogeography* 9: 339-344.

——— 1985. Distinguishing the effects of area and habitat type on island plant species richness by separating floristic elements and substrate types and controlling for island isolation. *Journal of Biogeography* 12: 527-535.

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs. *Science* 199: 1302-1310.

Flood, P.G. and Heatwole, H. 1986. Coral cay instability and species-turnover of plants at Swain Reefs, Southern Great Barrier Reef, Australia. *Journal of Coastal Research* 2: 479-496.

Fosberg, F.R., Stoddart, D.R., Woodroffe, C.D. and Sachet, M-H. (in prep.) *Plants of Suwarrow Atoll.*

Frisbie, R.N. 1944. *The Island of Desire*. New York: Doubleday Doran and Co. 234 pp.

Heatwole, H. and Levins, R. 1973. Biogeography of the Puerto Rican Bank: Species turnover on a small cay, Cayo Ahogado. *Ecology* 54: 1042-1055.

Helm, A.S. and Percival, W.H. 1973. *Sisters of the Sun.* London: Robert Hale and Co. 192 pp.

Kaplin, P.A. 1981. Relief, age and types of oceanic islands. *New Zealand Geographer* 37: 3-12.

Lee, M.A.B. 1984. Biogeography and ecology of atoll plants. *Progress in Physical Geography* 8: 509-522.

MacArthur, R.H. and Wilson, E.O. 1967. *The theory of island biogeography.* Princeton University Press. 203 pp.

Neale, T. 1968. *An Island to Oneself: the story of six years on a desert island*. London, Collins. 192pp.

Niering, W.A. 1963. Terrestrial ecology of Kapingamarangi Atoll, Caroline Islands. *Ecological Monographs* 33: 131-160.

Sachet, M-H. 1967. Coral islands as ecological laboratories. *Micronesica* 3: 45-49.

Scoffin, T.P., Stoddart, D.R., Tudhope, A.W. and Woodroffe, C.D. 1985. Exposed limestones of Suwarrow Atoll. *Proc. 5th Int. Coral Reef Congress* 3: 137-140.

Stoddart, D.R. 1962. Catastrophic storm effects on the British Honduras reefs and cays. *Nature* 196: 512-515.

——— 1963. Effects of Hurricane Hattie on the British Honduras reefs and cays, October 30-31, 1961. *Atoll Research Bulletin* 95: 1-142.

——— 1975a. Almost-atoll of Aitutaki: geomorphology of reefs and islands. *Atoll Research Bulletin* 190: 31-57.

——— 1975b. Vegetation and floristics of the Aitutaki motus. *Atoll Research Bulletin* 190: 87-116.

——— 1992. Biogeography of the tropical Pacific. *Pacific Science* 46:276-293.

——— and Fosberg, F.R. 1982. Species-area relationships or small islands: floristic data from Belizean sand cays. Rützler, K. and Macintyre, I.G. (eds.) The Atlantic barrier reef ecosystem at Carrie Bow Cay, Belize I. Structure and Communities. *Smithsonian Contributions to Marine Science* 12: 527-539.

——— , Woodroffe, C.D. and Fosberg, F.R. 1983. Substrate-specific species distributions on Suwarrow Atoll, central Pacific: implications for island biogeography theory. *Abstr. 15th Pacific Science Congress* 2:227-228.

Tudhope, A.W., Scofin, T.P., Stoddart, D.R. and Woodroffe, C.D. 1985. Sediments of Suwarrow Atoll. *Proc. 5th Int. Coral Reef Congress* 6: 611-616.

Whitehead, D.R. and Jones, C.E. 1969. Small islands and the equilibrium theory of insular biogeography. *Evolution* 23: 171-179.

Wiens, H.J. 1962. *Atoll environment and ecology*. Yale University Press. 532 pp.

Wood B.L. and Hay, R.D. 1970. Geology of the Cook Islands. *New Zealand Geological Survey Bulletin* 82: 1-103.

Woodroffe, C.D. 1986. Vascular plant species-area relationships on Nui Atoll, Tuvalu, Central Pacific: a reassessment of the small island effect. *Australian Journal of Ecology* 11: 21-31.

ATOLL RESEARCH BULLETIN

NO. 363

SECONDARY PLANT COVER ON UPLAND SLOPES MARQUESAS ISLANDS, FRENCH POLYNESIA

BY

B. G. DECKER

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992

CONTENTS

ABSTRACT

This monograph sheds light on the status of secondary plant cover, heretofore little known, on slopes between sea level and about 750m in the Marquesas Islands, a remote tropical Polynesian archipelago of high islands of volcanic origin situated in the dry tradewind zone of the South Pacific. Plant cover types are described and assigned to xerotropical, transitional and pluviotropical floristic zones determined in part by comparison with similar zones previously devised for Oahu Island, Hawaii.

In floristic detail, it describes the status of plant cover on the most readily visible lands, the slopes that rise above the valley bottoms and that are much disturbed by human activity, but not occupied with actual settlement and cultivation. Some ecological interpretations of recent disturbance history also appear.

Floristic and zonal vegetation comparisons with southeast Oahu cast the Marquesan field data into an instructive form that should be useful in the comparison of Marquesan plant cover with that of Hawaii and of other islands in the dry tradewind zones of the world.

SECONDARY PLANT COVER ON UPLAND SLOPES,

MARQUESAS ISLANDS,

FRENCH POLYNESIA[1]

BY

BRYCE GILMORE DECKER[2]

FOREWORD

The publication of this article has been delayed for nearly twenty years. Except for some changes in botanical nomenclature suggested by F. Raymond Fosberg of the Smithsonian Institution, the text has not been substantially revised to include changes in the Marquesas Islands that have occurred since then, nor reference to scientific work and botanical exploration in the Marquesas since the early 1970s. Much of the information in this monograph and more on the plant cover of houseyards and cultivated sites appears in my dissertation: *Plants, Man and Landscape in Marquesan Valleys, French Polynesia*; University of California, Berkeley (Geography), 1970.

THE MARQUESAS ISLANDS

The archipelago, comprising nine principal islands (Lat 7°50'S; Long 138°50'W), is politically part of French Polynesia (Polynésie française), which is an overseas *département* of France. The group lies about 1300 km NE of the entrepot for the country, Papeete, at Tahiti in the Society Islands.

Long accessible only by sea, a first aerial link with Tahiti and the outside world was established well after this study ended, with the completion of an airfield on Uahuka Island in 1970.

Total land area, about 1060 sq. km. (Adamson, 1936) approximates that of the single island of Tahiti (1040 sq.km.) and is about two-thirds the size of Oahu, the island on which Honolulu is located (1564 sq.km.). When the small area of these volcanic remnants is considered, their peaks rise to remarkable heights. Hivaoa, Nukuhiva and Uapou all exceed 1200m, an elevation comparable to the highest on Oahu. Most Marquesan topography is quite as ruggedly dissected and spectacular as Oahu's Waianae mountain

---

[1]Field research for this study in 1963-64 was supported by the Foreign Field Research Program conducted by the Division of Earth Sciences, National Academy of Sciences—National Research Council, and sponsored by the Geography Branch, [Office of Naval Research, Contract Nonr-2300 (09)].

[2]Department of Geography, University of Hawaii at Manoa, Honolulu, Hawaii 96822, U.S.A.

Manuscript received 4 November 1991

range, or the interiors of Tahiti and of other Pacific high islands with approximately similar geological histories.

The Marquesas share with Hawaii a dry tradewind landscape of arid lower slopes and moist high interiors that are always green with an important difference. Marquesan droughts sometimes last three to five years and may be very severe to both ecology and economy.

A mostly Polyesian population of about 5000 (4800 in 1962) supplements income from copra sales and public works with subsistence gardening, fishing and shooting of feral goats, cattle and sheep that freely roam the uplands above the deep valleys and canyons that contain all the villages and most of the cultivations.

FIELD WORK

During a broader study of plant cover as it reflects the influence of man (Decker, 1970), field work concentrated in and near two representative inhabited valleys; Puama'u Valley on NE Hivaoa Island, and Vaipaee Valley on Uahuka Island. Those islands are separated by 120km of open sea.

In the course of approximately nine months' residence, plant cover types were mapped in detail. Notes and voucher specimens documenting floristic composition were made in these and other localities on five islands. Some collections and data derive from a prior nine-months' residence as a private traveler in 1960. Sets of specimens have been deposited in herbaria in Hawaii (BISH), California (UC), Washington, D.C. (US), and Paris (P).[1]

PERTINENCE OF FRANK EGLER'S ECOLOGICAL WORK ON SOUTHEASTERN OAHU

Advantage has been taken of floristic and climatic similarities between the Marquesas and Hawaiian Islands to apply to the Marquesas a convenient scheme of vegetation description devised by Frank Egler for the island of Oahu, with some modification. Papy (1955) used Egler's approach in a comparable treatment of the vegetation of the Society Islands.

In the Marquesas, as in Hawaii, a secondary vegetation containing many species of wide tropical distribution, and introduced since the arrival of man, occupies most localities below 800-900 meters. An impressive number of such species is common to both archipelagos, particularly in the drier localities, as will be seen.

Climatically, both Hawaii and the Marquesas lie in regions of dry easterly tradewinds so that all low-lying land is subject to desiccation by prevailing winds that blow most of the time from the same quarter. The desiccation is most pronounced on slopes that lie in leeward rain shadows.

With elevation, the regional dryness is slaked by orographic showers that fall onto the heights and keep the mountains green.

---

[1]Abbreviations indicate herbaria as listed in Index Herbariorum.

Briefly stated, the moist-dry transition, so visible in the landscape and ecologically fundamental, is employed as an important vegetation boundary. In 1947, Frank Egler elaborated a xerotropical floristic area and xerotropical vegetation zones for SE Oahu (see fig. 1). His approach accommodated three important aspects of the secondary plant cover of Oahu, aspects generally shared in common with Marquesan plant cover: 1) the abrupt, conspicuous transition from dry to moist environments; 2) a distinct ecological segregation of species into two floras—pluviotropical and xerotropical—corresponding to their adaptations to one or the other ecological area; and 3) the confusing mosaic of structural types resulting from complex and unrecorded disturbance history.

Within each zone dominant species lend the various cover types a characteristic texture and morphology. But on Oahu, the dominant species were viewed by Egler as clearly xerotropical or pluviotropical. He saw them growing on either side of a moisture boundary that he mapped as a simple line. Thus, his main geographical demarcation relied upon an ecological criterion, the moisture boundary between the two zones.

In the arrangement of Marquesan zones and floras, the reader should note an important departure from Egler's arrangement for Oahu. I was not able to distinguish a moisture line as clearly as Egler did. In the Marquesan landscape, the transition between pluviotropical and xerotropical zones is marked by dominant cover types of its own. Accordingly, I describe a discrete Marquesan <u>transitional zone</u> and list a <u>transitional flora</u>.

Vegetation dynamics interested Egler, too, and he had much to say about the subject. In the time ordinarily available for a field study, the course of succession is impossible to predict. His approach assures that neither difficulty with tropical successional relationships that are obscure, nor details of disturbance history that cannot be known, need interfere with a logical arrangement and useful description of vegetation.

I use <u>plant cover</u> synonymously with <u>vegetation</u> in one strict sense of the latter: that is when vegetation refers to the entire complex blanket of plant life of a place. <u>Plant cover types</u> are visible elements that may be differentiated from the total mosaic of plant cover and mapped as discrete types.

THREE FLORAS

<u>The Xerotropical Flora</u>

In order to establish a xerotropical zone for the Marquesas, a floristic comparison is made here between Egler's lists of xerotropical species from southeast Oahu and mine from the Marquesas.

In the lists that follow, only Marquesan xerotropical species appear. The first two lists compare in a very general way the relative abundance of those xerotropical species common to both SE Oahu and the Marquesas. The third list includes the additional Marquesan species that do not appear in Egler's SE Oahu flora.

An interrogation point [?] precedes *Oxalis corniculata* and *Psilotum nudum* because they were seldom collected and then not as part of a distinctly xerotropical cover. I have omitted *Commelina diffusa*, which is pluviotropical and may have appeared in Egler's xerotropical flora in error. Critical taxonomic work remains for plants identified by genus alone. Where names have seen revisions, the name used in my dissertation appears here in parentheses.

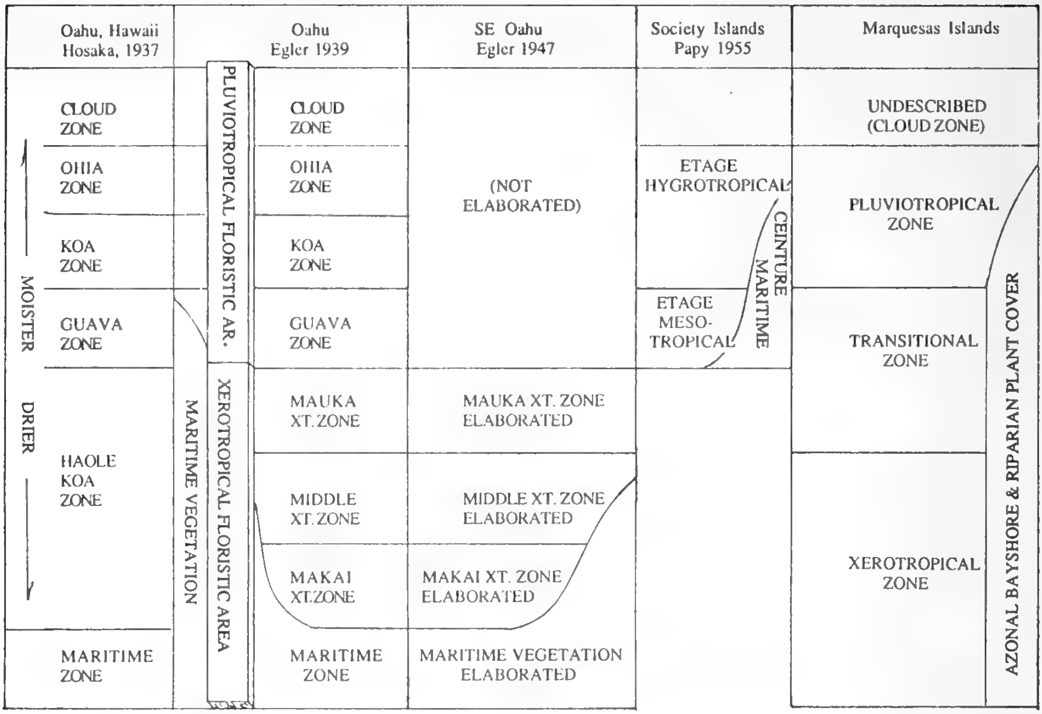


Figure 1. Marquesan Floral Zones Related to Earlier Work in Hawaii and the Society Islands.

<u>Explanation of Figure.</u> Egler (1939) described xero- and pluviotropical floras for Oahu, Hawaii, and extended to the whole of that island the vegetation zones described earlier by Hosaka (1937:201-211) for Kipapa Gulch, which naturally transects the gamut of Oahu vegetation zones. In a major monograph, Egler (1947) elaborated the xerotropical zones of southeastern Oahu. After tentative application of the xerotropical and pluviotropical concepts of Egler to Tahiti, Society Islands (Papy, 1948, not in figure), Papy (1955, fn., 176) recanted, after a climatological analysis indicated to him that the entire land area of the Society Islands was too moist to be called xerotropical. Papy did put the lee sides of the Society Islands into a mesotropical zone which appears equivalent to Egler's guava zone and at least part of my Marquesan transitional zone. Egler (1939,4; 1947, 405-406) emphasized the azonal character of maritime vegetation and Papy and I have followed suit. The pluviotropical guava zone reaches the shore on windward Oahu but not in the southeastern sector of that island. The pluviotropical zone extends to the shore in the Marquesas and, as Papy noted, in the Society Islands, too. Papy (1955, fn.,176) preferred the word <u>hygrotropical</u> to pluviotropical for etymological reasons, but rather different names seem appropriate for Papy's zones because he attempted to define them climatically in a way that Egler pointedly eschewed. Egler used the adaptations displayed by arrays of growing plants to define the moisture regimes at their sites. (Egler, 1947, pp. 391-295; Papy, 1954, 1955).

There are other symbols. An asterisk "*" precedes species common or widely distributed in the Marquesas; "(TR)" precedes species with ranges that extend into the transitional zone, described below. Locally established species are followed by a list of localities where they were observed. Species lacking a qualifying symbol or annotation are of occasional occurrence.

I. XEROTROPICAL SPECIES OF THE MARQUESAS WIDESPREAD OR DOMINANT IN SOUTHEAST OAHU:

Acacia farnesiana (local on Tahuata, Nukuhiva, Eiao)
(TR) **Ageratum conyzoides*
(TR) *Bidens pilosa*
(TR) **Cassia occidentalis*
**Cenchrus echinatus*
(TR) **Chrysopogon aciculatus*
**Cynodon dactylon*
**Dactyloctenium aegyptium*
Desmodium triflorum (local at Puamau football field)
**Eleusine indica*
(TR) **Emilia sonchifolia*
Eragrostis amabilis (*E. tenella*)
**Euphorbia hirta*
(TR) **Indigofera suffruticosa* (absent at Vaipaee)
Leucaena leucocephala (Egler's *L. glauca*; local on Uapou, Nukuhiva, & Hivaoa at Puamau)
**Macroptilium lathyroides* (*Phaseolus lathyroides*)
**Malvastrum coromandelianum*
(TR?) *Oxalis corniculata*
**Passiflora foetida* var.
Peperomia blanda (*P. leptostachya*)
Plumbago zeylanica
**Portulaca oleracea*
(TR?) *Psilotum nudum*
Ricinus communis
Setaria verticillata
Sonchus oleraceus
Tricholaena rosea (Egler's *T. repens*; local on Hivaoa, Uapou, Tahuata)
**Waltheria indica* (Egler's *W. americana*)
Xanthium strumarium (Egler's *X. saccharatum*)

The second list comprises Marquesan xerotropical species that were less abundant on SE Oahu, occurring there on less than 80% of Egler's field lists. It will be noted that some of these species are, however, common and widespread in the Marquesas.

Modifying symbols below are used as in the first list above.

II. MARQUESAN XEROTROPICAL SPECIES NEITHER COMMON NOR WIDESPREAD IN SOUTHEAST OAHU:

Amaranthus viridis
**Canthium odoratum*
(TR) *Capsicum frutescens*
Cardiospermum halicacabum

Catharanthus roseus
**Cyperus javanicus*
(TR?) *Cyperus rotundus* (local on Puamau football field; on Nukuhiva and Uahuka in villages)
**Digitaria setigera* (*D. pruriens*)
(TR) *Dodonaea viscosa*
(TR?) *Dolichos lablab* (apparent escape from cultivation at Puamau)
(TR) *Eugenia cumini* (introduced on all islands but widely naturalized only in vicinity of Bay of Traitors, Hivaoa)
Euphorbia prostrata
Gossypium barbadense
(TR) *Melinis minutiflora* (Nukuhiva, Hivaoa, Fatuiva)
(TR) **Morinda citrifolia*
Ocimum gratissimum
Panicum maximum
(TR) **Psidium guajava*
(TR) *Psidium guineense* (*P. guajava* and *P. guineense* were not distinguished in the field and many of the specimens remain unnamed pending study)
Salvia occidentalis (local at Taiohae on Nukuhiva)
(TR) **Synedrella nodiflora*
(TR) *Tecoma stans* (local, southern Nukuhiva)
Tephrosia purpurea
**Vernonia cinerea* (var. *parviflora* in Marquesas)

The enumeration of Marquesan xerotropical plants concludes with 45 more species that grow intimately along with the plants on the two lists above. None are listed by Egler from SE Oahu, but many of them are in fact common on Oahu and elsewhere in Hawaii. See, for example, the floristic enumerations for Hawaiian vegetation zones (Ripperton & Hosaka, 1942), game bird habitats (Schwartz & Schwartz, 1949), ecosystems (Fosberg, 1972), and Oahu dry-grass communities (Kartawinata & Mueller-Dombois, 1972).

III. MARQUESAN XEROTROPICAL SPECIES ABSENT FROM EGLER'S OAHU LISTS:

(TR) *Abrus precatorius*
Abutilon grandifolium
**Abutilon hirtum*
**Achyranthes aspera* (*A. indica*)
Aristida sp. (collected only at Oea on Nukuhiva)
Asclepias curassavica
**Caesalpinia bonduc*
Caesalpinia major
(TR) **Casuarina equisetifolia*
(TR) **Celastrus crenatus*
Celtis pacifica
(TR) *Cerbera manghas*
Cleome viscosa
(TR) **Colubrina asiatica*
**Cordia lutea*
(TR) *Cordia subcordata*
Eragrostis xerophila (native to Marquesas)

(TR) **Erythrina variegata*
Eugenia sp.
(TR) *Ficus prolixa*
Fimbristylis separanda (E. flank of Taiohae Bay, Nukuhiva)
Gossypium hirsutum var. or ssp.
(TR) *Guettarda speciosa*
Ipomoea macrantha (*I. tuba*)
Jatropha gossypifolia (local at Vaipaee)
Melochia pyramidata (Taiohae, Nukuhiva & Hakahetau, Uapou)
Ocimum basilicum
Ocimum sanctum (Hakehetau, Uapou)
**Panicum reptans* var *marquisense*
Peperomia spp, (in crevices of outcropping boulders)
(TR) *Phyllanthus amarus*
Pisonia grandis
(PT & TR) **Polypodium scolopendria*
**Rhynchosia minima*
Salvia coccinea (collected on Uahuka only)
(TR) **Sapindus saponaria*
(TR) **Sida acuta*
Sida hybrids (*Sida acuta* and *S. rhombifolia* are apparently hybridizing, according to F. R. Fosberg in personal communication.)
Sida paniculata (local on Tahuata, Uapou, Nukuhiva)
**Sida rhombifolia* (*)
(TR) *Thespesia populnea*
Tribulus cistoides
(TR) **Triumfetta rhomboides* (*T. bartramia*)
**Waltheria tomentosa* (Marquesan native species)
(TR) **Xylosma suaveolens* subsp. *pubigerum*

The Transitional Flora

Excepting the yards and gardens, certain areas in the transitional zone are as rich in species as any part of the lower elevations. Most of the plants are readily assignable either to the xerotropical or pluviotropical floras. A few very common species, however, lie athwart the transition: *Casuarina equisetifolia, Desmodium incanum, Miscanthus floridulus, Nephrolepis hirsutula, Premna serratifolia, Psidium* spp., *Sapindus saponaria, Xylosma suaveolens.*

The looming dominance of several of the latter in very visible cover types dictated the utility of a transitional zone and flora for descriptive purpose, although it departs from the elegant division that Egler was able to map for southeast Oahu. It may be argued that a similar transitional zone exists on Oahu; *Psidium guajava* is there so distributed, as perhaps also in Tahiti (See fig. 1). The visibly dominant species on Oahu cover types, however, were in Egler's (1947) view either xerotropical or pluviotropical, as already noted.

The list that follows is annotated as were the xerotropical lists above with the symbols "(XT)" and "(PT)" to denote xerotropical and pluviotropical species respectively.

THE TRANSITIONAL FLORA

(PT) *Aleurites moluccana* (in deep ravines and box canyons)
(XT) *Amaranthus viridis*
(PT, XT) *Bidens pilosa*
(XT) **Caesalpinia bonduc*
(XT) *Caesalpinia major*
(PT) **Canthium barbatum*
(XT) **Canthium odoratum*
(XT) *Capsicum frutescens*
(PT) *Carica papaya*
(XT) *Cassia occidentalis*
(XT) **Casuarina equisetifolia*
(XT) **Celastrus crenatus*
(XT) *Celtis pacifica*
(XT) *Cerbera manghas*
(XT) **Chrysopogon aciculatus*
(PT) *Coffea arabica*
(XT) **Colubrina asiatica*
(PT) *Commelina diffusa*
(XT) **Cordia subcordata*
(XT) **Cyperus javanicus*
(PT) **Cyperus kyllingia*
(PT) *Cyperus marquisensis*
**Desmodium incanum*
(PT) **Digitaria henryi* (zonal status doubtful)
(?) **Digitaria radicosa* (*D. timorensis*; adventive on open sites; zonal status doubtful)
(XT) **Digitaria setigera* (*D. pruriens*)
(PT) *Elephantopus mollis* (still spreading on Hivaoa, Nukuhiva & Fatuiva)
(PT) *Elephantopus spicatus*
(PT) *Emilia fosbergii* (*E. javanica*; extent of occurrence uncertain)
(PT) **Emilia sonchifolia*
(XT) **Erythrina variegata*
Eugenia sp.
(XT) *Eugenia cumini*
(PT, XT) **Ficus prolixa*
(PT) *Gleichenia linearis*
(PT) **Glochidion* sp.
(XT) *Guettarda speciosa*
(PT) *Hibiscus tiliaceus*
(PT) **Hibiscus tiliaceus* var. *sterilis*
(XT) **Indigofera suffruticosa*
(PT?) *Ipomoea* sp.
(XT) *Ipomoea macrantha* (*I. tuba*)
(PT) *Ipomoea obscura*
**Miscanthus floridulus*
(PT, XT) **Morinda citrifolia*
Morinda umbellata var. *forsteri* (col. Puamau only)
(PT) **Nephrolepis biserrata*
(PT) **Nephrolepis hirsutula*
(XT) **Ocimum gratissimum*

(XT) *Ocimum sanctum* (collected only on Uapou)
(PT) *Oplismenus compositus*
(?) *Oplismenus hirtellus*
(PT) **Pandanus tectorius* sensu lato
(XT) **Panicum reptans* var. *marquisense*
(XT) *Passiflora foetida* var.
(XT) *Phyllanthus amarus*
(XT) *Pisonia grandis*
(PT, XT) **Polypodium scolopendria*
**Premna serratifolia* (*P. tahitensis*)
(PT, XT) **Psidium guajava*
(PT) **Psidium guineense*
(PT) *Santalum insulare* (native to Marquesas)
(XT) **Sapindus saponaria*
(XT) **Sida acuta*
(PT) **Stephania hernandifolia* (not collected at Puamau)
(XT) **Synedrella nodiflora*
(XT) **Thespesia populnea*
(XT) **Tricholaena rosea* (locally established on Hivaoa, Uapou, and Tahuata)
(XT) **Triumfetta rhomboidea* (T. bartramia)
(XT) **Vernonia cinerea*
(PT) *Wikstroemia coriacea* (*W. foetida*)
(XT) **Xylosma suaveolens* subsp. *pubigerum*

The Pluviotropical Flora

Egler (1939) left the pluviotropical vegetation of Oahu without detailed floristic lists such as he subsequently (1947) published for the southeastern Oahu xerotropical. Several prominent Oahu pluviotropical species were mentioned, however, that are abundant enough for indicator use in the Marquesas. They include *Aleurites moluccana*, Coffea arabica, *Commelina diffusa*, *Cordyline fruticosa*, *Gleichenia linearis*, *Paspalum conjugatum*, and *Psidium guajava*.

Psidium guajava seems to be primarily pluviotropical, but it extends well into the xerotropical zone and is prominent in the transitional zone. In rainy periods *Commelina diffusa* likewise may be seen in ground cover of the transitional zone.

The other species seem to be reliable Marquesan pluviotropical zone indicators, particularly *Paspalum conjugatum* and *Gleichenia linearis*. On Uahuka, however, *P. conjugatum* has not yet become established and *Coffea arabica* remains only locally naturalized. With the notable exception of *G. linearis*, which forms conspicuous and extensive fernbrakes, none of these Hawaiian indicator species is widely dominant in the Marquesas. In addition to *G. linearis*, the characteristic indicator of pluviotropical conditions in the uplands is *Hibiscus tiliaceus*.

The enumeration of pluviotropical plants below includes few native Marquesan species, because they were not encountered in the sampled localities. It would be right to expect them because the higher pluviotropical zone abuts the cloudy heights that are rich in species peculiar to the archipelago.

The list does comprise the common plants from secondary pluviotropical plant cover types subject to disturbance by grazing, trampling and fire in the areas studied or

traversed. The list should grossly delimit the pluviotropical zone on all the inhabited Marquesas islands.

Where the range of a species extends into the transitional zone, its name is preceded by "(TR)" as in the foregoing lists. Again, asterisks denote the widespread species most often encountered.

Adenostemma lanceolata (A. lavenia)
Ageratum conyzoides
Aleurites moluccana
Alocasia macrorrhiza
Asplenium nidus
Athyrium sp.
Barringtonia asiatica
(TR) *Bidens pilosa*
Calophyllum inophyllum
**Canna indica* (not common in uplands and fallow)
(TR) **Canthium barbatum*
(TR) **Carica papaya*
**Centotheca lappacea*
**Cocos nucifera*
(TR) **Coffea arabica*
(TR) **Commelina diffusa*
Cordyline fruticosa
Cyathula prostrata
Cyperus brevifolius
(TR) *Cyperus kyllingia*
(TR) *Cyperus marquisensis* (native species)
Desmodium heterocarpon var. *strigosum*
(TR) **Digitaria henryi* (on open trampled ground; PT status doubtful)
Dioscorea alata
Dioscorea bulbifera
Dioscorea esculenta var. *fasciculata*
(TR) **Elephantopus mollis* (limited distribution on Fatuiva, Hivaoa & Nukuhiva)
(TR) **Elephantopus spicatus*
(TR) *Emilia fosbergii* (*E. javanica*)
(TR) **Emilia sonchifolia*
Fimbristylis nukuhivensis (native species)
Freycinetia spp. (at least two native spp.)
(TR) **Gleichenia linearis*
(TR) *Glochidion* sp.
(TR) **Hibiscus tiliaceus*
(TR) **Hibiscus tiliaceus* var *sterilis*
Histiopteris incisa
**Inocarpus fagifer* (*I. fagiferus*)
(TR) *Ipomoea* sp.
(TR) *Ipomoea obscura*
**Lycopodium cernuum*
**Mangifera indica*
Marattia sp.
(TR) **Morinda citrifolia*
Nasturtium officinale
(TR) **Nephrolepis biserrata*

(TR) **Nephrolepis hirsutula*
(TR) **Oplismenus compositus*
(TR) **Pandanus tectorius* sensu lato
**Paspalum conjugatum*
**Paspalum paniculatum*
Peperomia spp.
Piper latifolium
Pipturus argenteus
(XT, TR) *Polypodium scolopendria*
(XT, TR) **Psidium guajava*
(TR) *Psidium guineense*
Pteris sp.
(TR) *Santalum insulare* (native species)
Schizostachyum sp.
Sphenomeris chinensis
Spondias dulcis
(TR) *Stephania hernandifolia*
Tacca leontopetaloides
Tectaria marchionica (native species)
Terminalia catappa
**Thelypteris opulenta*
Urena lobata
Vanilla planifolia
Weinmannia sp.
(TR) *Wikstroemia coriacea* (*W. foetida*)
Xanthosoma sagittifolia

PROMINENCE OF STRAND SPECIES IN FORESTS OF THE INTERIOR

A remarkable feature of the Marquesan inland secondary forests is the persistent dominance in them of species widely associated in tropical countries with the saline environments of the shore, or, when not distinctively plants of the shore environments, at least demonstratively capable of dispersal by ocean currents, as shown by Guppy (1906, 528-531; 1917, 86-87).

Egler hesitated to elevate the distinctive Oahu maritime plant community of salt-tolerant species to a zonal rank comparable to his xerotropical and pluviotropical. He saw that many maritime species thrived in inland localities miles away from the shoreline. "...[the] mountainward ... boundary [of the maritime zone] is generally independent of ecologic controls and is very indefinite. That is, edaphic and atmospheric factors, although they play a role in limiting the seaward ... extension of non-maritime communities, do not on the other hand control the [mountainward] limit of most strand plants. Fortuities in terrestrial migration account for the highly irregular and unpredictable distribution of strand communities." (Egler 1947, 405)

Egler also emphasized that "this flora, always thought to be remarkably adapted for transportation by currents, is perhaps as remarkable for its relative lack of adaptations for terrestrial migration." (Egler 1947, 405-406)

A number of Marquesan plants fit that description. They regenerate well in Marquesan inland sites and can be called widely naturalized there:

Caesalpinia bonduc
Colubrina asiatica
Cordia subcordata
Erythrina variegata
Guettarda speciosa
Ipomoea macrantha
Hibiscus tiliaceus
Morinda citrifolia
Pandanus tectorius sensu lato
Premna serratifolia
Sapindus saponaria
Thespesia populnea

Most of those species grow in forests below about 500m, but the dominance of at least two, *Hibiscus tiliaceus* and *Pandanus tectorius*, extends to the very margins of the cloud forest.

Plate 1: Forest dominated by *Pandanus tectorius* and *Hibiscus tiliaceus*. *Gleichenia linearis* fernbrake occupies the ridge crest above. Vaikivi, interior of Uahuka Island.

In Oahu, Egler found little evidence of reproduction of the maritime species transported inland. In obvious contrast, in the Marquesan interior, regeneration of a significant number of maritime and large- or buoyant-seeded plants has not been hampered in any obvious way by presumed deficiencies in dispersal mechanisms nor by competition from other species.

The strand species display every evidence of permanence in the upland vegetation. It is interesting that they vary considerably in their apparent moisture requirements and segregate themselves into the three Marquesan floral zones.

It is conceivable that ancient Polynesians carried at least some of these strand plants inland. All were employed in the aboriginal economy. Their inland prominence reinforces a view that aboriginal alteration of the vegetation below the cloud zone must have been profound, coincident with the establishment there of the shore species. The primeval vegetation would have been suppressed in the clearing for cultivation of these and other useful but less persistent plantings, and by the use of fire.

THE NATURALIZATION OF COFFEE AND OTHER CULTIVATED PLANTS

Most of the cultivated plants of the world are heliotropic. It is not at all unusual to see certain of them escape garden or field to grow adventitiously in sunny, open sites. That is true of many garden ornamentals, most of which have short evolutionary histories in cultivation and retain some aggressiveness in the wild state. *Plectronia scutellarioides* (*Coleus blumei*) and *Catharanthus roseus* are excellent examples from the Marquesas. Presumably all historically introduced, some of the conspicuous upland fugitives from cultivation include:

Acacia farnesiana
Bixa orellana (in dry stream courses)
Caesalpinia pulcherrima
Canna indica
Coffea arabica
Eugenia cumini (especially around the Bay of Traitors, Hivaoa)
Eugenia uniflora (locally established around Bay of Traitors, Hivaoa)
Melia azedarach
Nicotiana tabacum
Ocimum basilicum
Psidium spp.
Ricinus communis
Salvia coccinea (Uahuka)
S. occidentalis (Taiohae, Nukuhiva)
Sorghum halepense
Stenolobium stans
Tricholaena rosea
Vitus sp. (at Hanaiapa, Hivaoa)

The phenomenal status of *Coffea arabica* as a thoroughly naturalized tree in most of the islands holds some ecological interest. *C. arabica* is one of the few cultivated species that prefers a semi-shaded habitat. In the Marquesas there are exceedingly few real ombrophiles at the lower elevations. *C. arabica*, with either some obscure measure of

aggressiveness in shaded situations or utter lack of local competition for such a niche, has effectively formed a shrubby understorey in the older secondary forests. Did nothing like it grow in that niche before its introduction in the nineteenth century? The understorey of small coffee trees, their own seedlings sprouting densely, is most remarkable beneath the dense forest canopy of *Hibiscus tiliaceus* in the humid back valley ravines, There, in the deep shade, virtually all other macroscopic green plant life is absent, but *Coffea* thrives.

THE XEROTROPICAL ZONE AND XEROTROPICAL COVER TYPES

A xerotropical vegetation dominated by low grasses and suffrutescent herbs prevails over extensive areas on most of the islands, particularly at the lower elevations, above or adjacent to coastal cliffs, in places well removed from the islands' central heights. As a rule, the suffrutescent plants grow most densely in ravines on sheltered, less disturbed slopes, and toward the interior. A number of xerotropical shrubs and trees are also encountered toward the interior and in sheltered ravines. Relic xerotropical forest with closed canopy exists outside the study area on Hatutaa and in places on leeward Nukuhiva.

The gentle sweep of broad interfluves in the xerotropical zone of southwestern Uahuka, the weathered remnants of cinder cones, and the grey, yellow-brown of the sparse vegetation are reminiscent of Easter Island landscapes, even to the dark coastal cliffs above a reefless white and purple sea. In the Puamau study area, by contrast, there is little xerotropical cover and it is confined to the very steep slopes of the gravely denuded mountain, Namana, on the northwestern side of the bay.

Except in relic localities inaccessible to foraging animals, the present xerotropical plant cover reflects in obscure degrees the influence of those animals. Soil erosion associated with their activity has utterly denuded plant and soil cover from many localities. The spread of certain historically introduced plants has almost certainly been facilitated by the presence of goats, sheep, cattle, horses and asses.

Animals have gravely denuded terrain in these localities: windward Fatuiva, southern Tahuata, northwestern and eastern Hivaoa,northern Uahuka, northeastern Uapou, western and northwestern Nukuhiva, and most of the entire islands of Eiao and Mohotane.

The influence of fire in this zone is problematical. No burning was observed of the xerotropical cover, but it is surely combustible in drought, and residents report that fires do occur. Both heavy grazing and a desire to leave forage for the animals may have served to reduce the incidence of casual burning of the range. The xerotropical zone constitutes the most significant grazing range on most islands.

Dominance of individual species varies considerably from place to place, although the whole floras of the xerotropical cover do not differ much from island to island. Certain species, by their local dominance, alter the physiognomy of a landscape. *Indigofera suffruticosa*, for example, introduced in historical time, had assumed wide dominance in the feral cattle, horse and goat ranges in northwestern Hivaoa west of Hanamenu in 1963, affording to that inclined plateau district a soft verdure quite in contrast with the barren, sparsely vegetated aspect of similar slopes elsewhere. In northeastern Hivaoa, a densely-growing grass, *Tricholaena rosea* (see discussion below) was rapidly colonizing the xeric slopes. Invading more slowly, the whipstem tree, *Leucaena leucocephala* has formed dense thickets over much of southern coastal Nukuhiva since its introduction in the nineteenth century (Drake 1893, 58-59). Similarly, a shrub with succulent branches, *Jatropha gossypifolia*, has begun to form its malodorous thickets on the steep slopes that flank the village of Vaipaee, on Uahuka.

<u>Seaward Xerotropical Cover</u>

In the driest outermost xerotropical localities two species are almost always present in some abundance: the low grass *Panicum reptans* and suffrutescent, sparingly-branched *Waltheria indica*. Several other common species usually combine with those two:

Abutilon hirtum
Cassia occidentalis
Cenchrus echinatus
Euphorbia hirta
Malvastrum coromandelianum
Ocimum gratissimum
Passiflora foetida var.
Portulaca oleracea
Rhynchosia minima
Sida rhombifolia
Vernonia cinerea

Plate 2: Seaward xerotropical plant cover on grazed terrain, southern Uahuka Island. The view is toward the south, overlooking the narrowed lower reach of Vaipaee Valley.

In general, the suffrutescent herbs and shrubs are more common in ravines and on undenuded, steep slopes where thickets may be dense enough to defy easy penetration by humans and large animals. Species are listed below in approximate order of observed frequency, with species reference to southwestern Uahuka, except as noted.

Grasses and Sedges:
- *Panicum reptans*
- *Cenchrus echinatus*
- *Tricholaena rosea* (obs. only on Hivaoa, Tahuata, Uapou)
- *Cynodon dactylon*
- *Dactyloctenium aegyptium*
- *Digitaria setigera* (D. pruriens)
- *Setaria verticillata*
- *Eragrostis amabilis* (*E. tenella*)
- *Fimbristylis separanda* (seen only at Taiohae)

Herbs:
- *Rhyncosia minima*
- *Vernonia cinerea*
- *Euphorbia hirta*
- *Portulaca oleracea*
- *Passiflora foetida* var.
- *Synedrella nodiflora*
- *Ageratum conyzoides*
- *Salvia coccinea* (seen only on Uahuka)
- *Amaranthus viridis*
- *Asclepias curassavica*
- *Cleome viscosa*
- *Euphorbia prostrata*
- *Ipomoea obscura* (seen only at Puamau)
- *Tribulus cistoides*
- *Xanthium strumarium*

Suffrutescent Herbs:
- *Waltheria indica*
- *Sida rhombifolia*
- *Malvastrum coromandelianum*
- *Abutilon hirtum*
- *Cassia occidentalis*
- *Ocimum gratissimum*
- *Macroptileum lathyroides* (*Phaseolus lathyroides*)
- *Sida paniculata* (seen only at Nukuhiva, Uapou, and northeastern Tahuata)
- *Catharanthus roseus*
- *Sida acuta*
- *Sida hybrids*
- *Triumfetta rhomboidea* (*T. bartramia*)
- *Phyllanthus amarus*
- *Melochia pyramidata* (seen only on Nukuhiva and Uapou)
- *Ocimum sanctum* (Uapou only)

Shrubs and Trees:
- *Gossypium barbadense*
- *Gossypium hirsutum* var. *taitense*

Gossypium hybrids[1]
Jatropha gossypifolia (only at Vaipaee on Uahuka)
Waltheria tomentosa (*W. lophanthus*)
Cordia lutea
Gossypium hirsutum var. (collected Uahuka only)
Tephrosia purpurea
Ficus prolixa
Leucaena leucocephala (established on Nukuhiva, Uapou, and locally at Puamau, on Hivaoa)
Acacia farnesiana (locally established at Vaituha on Eiao; Taiohae, Nukuhiva; & Vaitahu, Tahuata)
Tamarindus indica (occasionally planted)
Albizia lebbeck (occasionally planted)

Inland Xerotropical Cover

This cover type lies between the seaward xerotropical and transitional cover types. It embraces most of the species listed above for the seaward xerotropical cover and is notably enriched by several shrubs and trees. Most of the species listed below also grow farther inland, in the transitional cover types, but these listed extend well seaward into the xerotropical zone beyond the farthest seaward salients of the transitional cover types.

Abrus precatorius
Caesalpinia bonduc
Caesalpinia major
Celastrus crenatus
Celtis pacifica
Chrysopogon aciculatus
Colubrina asiatica
Eugenia sp.
Guettarda speciosa
Ipomoea macrantha (*I. tuba*)
Morinda citrifolia
Polypodium scolopendria
Psidium guajava
Psidium guineense
Sapindus saponaria
Sorghum halepense (zonal status doubtful; seen at Puamau, on Hivaoa, only)
Thespesia populnea

Along the upland bordering Vaipaee canyon to the east, north of Tahoatikikau crater, the topography lies virtually level upon a steep precipitation gradient. It is possible there to distinguish a broad range of vegetation transition. Open woodland stands of *koku'u* (*Sapindus saponaria*) may be seen extending from the densely wooded transitional zone into inland xerotropical cover. Among these trees and between individuals and clumps of shrubs a dense cover of the suffrutescent herbs is characteristic. Excepting where animals traverse such cover frequently and create paths, penetration is arduous. *Ocimum gratissimum*, *Sida* spp. and *Triumfetta* are dominant at Vaipaee. *Indigofera suffruticosa*, abundant in such localities on other islands, is conspicuously absent here.

---

[1]Introgressive hybridization apparently occurs between the native *Gossypium hirsutum* variety and the introduced, naturalized *G. barbadense*, according to Paul Fryxell in personal correspondence.

Where density of the brushy canopy thins sufficiently to admit sunlight, typical low-growing xerotropical grasses and herbs cover the ground beneath.

In open, sunny places where animals congregate and along upland trails, *Malvastrum coromandelianum* is conspicuous, along with *Cynodon dactylon*, *Euphorbia hirta*, *Cenchrus echinatus*, *Dactyloctenium aegyptium* and less commonly *Amaranthus viridis* and *Euphorbia prostrata*. After prolonged rains these same open sites support an ephemeral explosive growth of annuals, and certain perennial pluviotropical heliophiles including *Vernonia cinerea*, *Ageratum conyzoides*, *Portulaca oleracea*, *Sida* spp., *Emilia sonchifolia*, *Elephantopus spicatus*, *Cyperus kyllingia*, and *Digitaria henryi* (Hivaoa only).

The onset of rainy weather also favors the suffrutescent herbs, and a usual public works project involves cutting away from trails the rank thickets of *Ocimum gratissimum*, *Indigofera suffruticosa* and *Triumfetta rhomboides* that appear in the course of a few moist weeks.

Plate 3: Transitional forest cover gives way to inland xerotropical cover on the far slope; view toward southwest overlooking Vaipaee valley 1 km above the village; camera's elevation about 180m.

Denuded Xerotropical Slopes

Whatever the vegetation cover of Mt. Namana, northwest of Puamau Bay, may once have been, its dike-shot brown aretes, cliffs, and buttress ridges appear nearly barren today, utterly stripped of soil; yet groves of large trees remain in deep ravines and on some of the gentler slopes. In a narrow zone between the groves and the highest denuded slopes, exposures of red-yellow soil, rilled by rainwash, announce the presence of goats and the persistence of denudation processes that began in the nineteenth century. Few observant travelers have failed to note the association of goats and sheep with degradation

of soil and vegetation in places that are either remote from habitation or comparatively inaccessible to hunters because of steep and otherwise difficult, broken terrain.

The condition of Mt. Namana, razed by goats and erosion, is typical of fully the eastern third length of Hivaoa, which is mostly denuded, barren mountainous country above imposing coastal cliffs. Clinging here and there to the brown, rocky slopes are large, solitary banyans called *aoa* (*Ficus prolixa*). Their spreading canopies incline parallel to the prevailing slope, and in these situations, they lack their usual pendant aerial roots. The contrast between the sparkling green foliage of these massive pale-trunked giants and the parched barren setting is as arresting as the sad reality that most of the growth that once surrounded the trees has vanished. The *aoa* seems to survive by virtue of a remarkable, proliferated system of ramifying roots that strike off from the base of the trunk along the rocky ground to seek crevices often some meters distant.

Apart from the banyans, the plant life on these denuded surfaces is scant. In crevices of weathered rock, once apparently a subsoil "C" horizon, one finds scattered depauperate individuals of *Waltheria indica*, *Panicum reptans*, *Abutilon hirtum*, *Cassia occidentalis*, *Euphorbia hirta*, *Vernonia cinerea*, and *Ageratum conyzoides*.

Turfs

Grassy turf formation, which constrains soil erosion on certain maritime slopes heavily used by animals, was noted in several localities around Puamau Bay. The turfed sites lie before salt-laden sea breezes at low elevation, on interfluves above sea cliffs. Several species of low-growing rhizomotous grasses participate: *Panicum reptans*, *Digitaria henryi*, *Dactyloctenium aegyptium* and *Cynodon dactylon*. On Uahuka, turfs of *Chrysopogon aciculatus* were noted in a similar maritime locality just east of Hokatu village. In general, *C. aciculatus* is associated with more moist conditions than commonly prevail on animal ranges near sea level. It is worth mention that where some soil remains, and granted favorable growing weather, a spontaneous pioneer revegetation of denuded slopes in the xerotropical zone proceeds rapidly after the animals are removed.

Grass Cover, *Tricholaena rosea* Type

Tricholaena rosea, a grass of tropical African origin, was reportedly brought from Tahiti to northeastern Hivaoa around 1950 by the late Edouard Friedman of Puamau, where it became known as *mutie etua*, or "Edouard's grass".

Since then, its spread has been phenomenal. The grass entirely covers all the xerotropical slopes between Eiaone and Hanapaoa to the west of Puamau, and well-established patches were noted all along the northern coast of Hivaoa from Natue to Hanamenu. It has been introduced on at least two other islands, Tahuata and Uapou.

Tricholaena does not seem to thrive in the driest seaward sectors; in fact, it grows inland on open sites well into the transitional zones.

An example of replacement of transitional zone vegetation by *T. rosea* was related by a credible observer on Hivaoa. In the valley of Eiaone, just west of Puamau, Mr. Henry Lie, a resident there for fifty years, has watched *Miscanthus floridulus* (discussed below) a conspicuous tall grass disappear from the valley's precipitous western flank under grazing pressure from his goats and sheep, only to witness a subsequent invasion of the same locality by *T. rosea*.

Similarly, patches of *Tricholaena rosea* may be seen in openings within the *Miscanthus* grass cover at Puamau, although the sequence of disturbance and revegetation there is unknown. *Tricholaena* also grows sporadically even in the pluviotropical *Gleichenia* fernbrakes along ridgecrest trails.

Where it is well-established, *T. rosea* grows 50-100cm tall with numerous branching culms in clumps spaced closely together so that unbroken stands of the grass result. The usual xerotropical shrubs and suffruticose herbs remain visible in the observed *Tricholaena* stands, but less abundantly than in typical xerotropical cover elsewhere. The capacity of this grass to invade sparsely vegetated, eroding uplands must be regarded as auspicious as long as unconstrained foraging animals move freely over their ranges.

The advent of *mutie etua* is much appreciated in Puamau where suitable horse forage is ever in short supply, as in all the larger humid valleys. For that reason alone, one might predict a rapid dissemination of the grass over the archipelago.

THE TRANSITIONAL ZONE AND TRANSITIONAL COVER TYPES

The vegetation of the transitional zone, like that of the adjacent zones, occupies diverse well-drained land at a wide range of elevation. In its present condition, the zone is characterized by more woody growth than prevails in the xerotropical zone and especially by the distinctive *Miscanthus floridulus* tall grass cover. Salients of transitional vegetation extend down ravines into the xerotropical zone and penetrate along rising ridgecrests into the pluviotropical zone.

Transitional cover type are physiognomically diverse, occur in mosaic, and reflect a corresponding diversity of land types and kinds of disturbance.

For example, at Puamau, the crest along one of the prominent ridges may be taken as typical. From a point in mid-valley, the ridge rises to abut the back wall of the great Puamau amphitheatre. Flanks drop sharply to either side of the narrow crest. Substrates along the crest include surfaces as varied as rock outcrops, old Polynesian stone platforms, excavated pit defenses, and deep lateritic soil. Grazing, burning, traffic by animals and humans, and even some clearing and planting complicate the recent disturbance history. On such a ridge, nearly all the transitional cover types may be represented: forest, scrub, *Casuarina* groves, *Pandanus* groves, *Miscanthus* tall grass, *Tricholaena* grass, along with patches of pluviotropical cover—*Gleichenia* fernbrake, and saliants of *Hibiscus* forest that here and there rise from the more humid ravines to overtop the ridge.

At Vaipaee, transitional vegetation occupies a large fraction of that basin along a crescentic belt that intersects the axis of the valley about half a kilometer above the village. The crescent curves to the north and east to include most of the western and northern flanks of the Vaipaee drainage.

Transitional Cover on Grazed Ranges

On the slopes of certain interfluves marked by animal activity and active erosion scars in friable, yellow-red, residual soil, the relatively dense cover afforded by suffrutescent herbs in the inland xerotropical zone gives way to a more open transitional cover of low grasses, herbs and shrubs. Locally, the low fertility seems affirmed by a turf of *Chrysopogon aciculatus* in which the shrubs and suffrutescent herbs appear scattered, spindly, and comparatively small. The latter include *Psidium* spp. *Morinda citrifolia*, *Triumfetta rhomboides*, *Waltheria indica*, *Desmodium incanum*, *Indigofera suffruticosa*

(not yet introduced at Vaipaee in 1963), and the fern *Polypodium scolopendria*. Another fern, *Nephrolepis hirsutula*, is the only other plant in the herbaceous assemblage that sometimes approaches a status co-dominant with *Chrysopogon aciculatus*. Toward the moist interior, fewer and fewer xerotropical species occur. Unforested, grazed areas grade into a trampled *Gleichenia* fernbrake. *Mangifera indica* occurs sporadically and often, along trails. That tree is not apparently as subject to the depauperate chlorosis that here afflicts the few other scattered trees, notably *Hibiscus tiliaceus* and *Pandanus tectorius*.

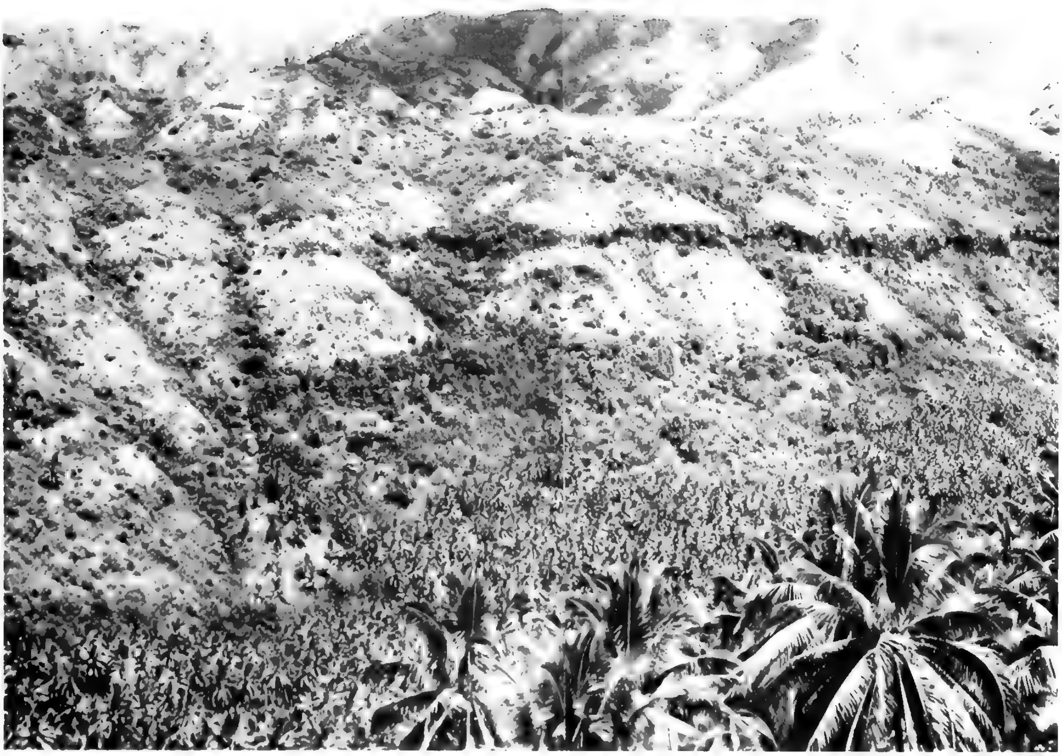


Plate 4: Transitional landscape, central Vaipaee valley, view toward northwest. The nearer slope displays little evidence of fire or other disturbance in recent years. *Miscanthus floridulus* tall grass (light tone) is mixed with growth of woody scrub. Compare it with far upper right (summit elevation 620m), where *Miscanthus* was burned over about three years before the photo was taken in 1964. Gentler slopes on the nearer ridgecrest (elevation about 275m) are no longer grazed and its transitional range is reverting to scrub and wood, but *Miscanthus* is still absent. Transitional forest on colluvium below *Miscanthus* covered slopes is perhaps 20 to 30 years old, as are the coconut palms in the valley bottom. Vertical jointing appears in the prominent stratum at mid-slope. Prevailing wind blows from right to left; the moister area is to the right, the drier to the left.

Other herbs occur in transitional range cover in varying abundance: *Ageratum conyzoides*, *Cyperus brevifolius*, *C. javanicus*, *C. kyllingia*, *Passiflora foetida*, *Synedrella nodiflora*, *Vernonia cinerea*.

Another upland grass, *Paspalum paniculatum*, enters grazed cover very prominently on Nukuhiva and to some extent on Hivaoa and other islands, but not at all at Vaipaee, where it is not yet established. *Tricholaena rosea* invades these localities at Puamau. Another recently introduced grass, *Melinis minutiflora*, had become similarly established among transitional range species in one locality above the bluff just east of the Catholic mission compound in Puamau.

Transitional Scrub

In the ravines and swales below the transitional ranges and wherever the transitional forest thins, a cover of typical transitional scrub appears.

The shrubs and small trees most abundantly seen are *Psidium guineense*, *P. guajava*, *Celastrus crenatus*, *Colubrina asiatica*, *Premna serratifolia*, and *Morinda citrifolia*. All of them at times approach the stature of trees, even *Colubrina*. When crowded, clambering *Celastrus* sometimes grows several meters up through the foliage of other plants, deriving enough support from its neighbors to acquire arborescent bulk. In addition, the usual trees of the transitional zone grow scattered among the shrubs.

A characteristic ground cover accompanies the transitional scrub where the canopy admits sufficient light for *Nephrolepis hirsutula*, *Desmodium incanum*, *Polypodium scolopendria*, and *Indigofera suffruticosa*. Locally, *Indigofera* assumes dominance, as does *Tricholaena rosea*, encroaching upon such open scrub at Puamau.

Additionally, where the scrub is traversed by trails, virtually all the common weedy herbs and grasses tolerant of upland soils appear in the ground cover along the way.

Tall Grass Cover of *Miscanthus* (*Kakaho*)

It did not reach Hawaii, but on other xeric high islands across the central Pacific from the Marianas to Mangareva, *Miscanthus floridulus* is the principal and aboriginal constituent of tall grassland maintained by periodic burning. Conspicuous wherever they arise in the Marquesas, broad swaths of the straw-yellow (green only after prolonged rainy weather) *kakaho* grass occupy ascending buttress ridges and other steep slopes above almost every Marquesan valley.

As one of the more dramatic elements in the Marquesan landscape, the rising swaths of tall grass and their combustibility did not escape the notice of at least one early observer, suggesting the probable antiquity of the aboriginal practice of burning, on which the continued maintenance of this distinctive cover seems to depend.

The first clear record of burned vegetation was made by Georg Forster (II, p.9) from the deck of the Resolution off Tahuata in 1774, but he did not note the nature of the burned vegetation. William Crook was the first to write, in 1797-1799, that on the slopes around Resolution Bay (Vaitahu, at Tahuata I.), "...the inferior ridges produce only reeds." (Sheahan 1952; cxl,cxlv). Crook's Marquesan vocabulary offers the word *kaukahhu* for reed (ibid., lxxv), which term appears equivalent to the modern *kakaho*. His reeds were almost surely *Miscanthus floridulus*, and it may be noted that his description of the "inferior ridges" still applies at Vaitahu, almost two centuries later.

Some months later, after Crook had removed to Nukuhiva, in the northern Marquesas, he observed there a burning of similar slopes.

> "About the month of August ... The appearance of the Soil upon these inferior ridges was barren; and they were only covered with burned Grass or Reeds. These are often set on fire, toward the lower part of the ridge, from whence the flame naturally spreads to the higher Ground." (Sheahan 1952, clxxiv).

Miscanthus floridulus attains a height of over two meters as a dominant in its typical transitional zone stands. In dense growth, penetration is arduous because of the stiff cane-like culms and microscopically serrate leaf margins that lacerate the flesh. Within the transitional zone it often gives way quite abruptly to forest or scrub. At the unforested margins of its range, it grades into the suffrutescent herbs and scattered shrubs of the inland xerotropical cover, or, on the moist side, into pluviotropical *Gleichenia linearis* fernbrake. At both these extremes of its range, it tends toward scattered, depauperate clumps that attain lesser heights—1 to 1 1/2 m or less.

The woody species that grow in some of the *kakaho* stands are all typical of the transitional zone. Most often seen are the *Psidium* spp. Less abundant but still common are *Morinda citrifolia*, *Celastrus crenatus*, *Pandanus tectorius*, *Hibiscus tiliaceus*, *Xylosma suaveolens* and *Casuarina equisetifolia*. Several of the species acquire unusually attenuated habits as stems lengthen to overcome shading by the grass: *Psidium*, *C. crenatus*, and *H. tiliaceus*.

Certain *kakaho* stands are so full of woody growth as to appear moribund, suggesting a successional trend toward transitional thicket or forest should the growth remain long free of fire. Excellent examples are the mixed *kakaho* and thicket on the western flank of Vaipaee canyon between the upper village and the great bend of that valley. Where the grass had burned in recent years, as in the extreme northwest corner of the valley, the shrubs were not so much in evidence.

According to local informants, the *kakaho* in the latter locality was swept by fire in the drought period preceding 1963.

Another striking feature of *Miscanthus* stands is their confinement to very steep slopes. Because the grass does grow here and there on gentle slopes, the prevalent occurrence is not easily explained on any obvious edaphic basis.

The key to the problem seems to be that grazing stock are excluded from these tall grasslands by both man and the terrain. Cattle and horses are typically present in uplands near villages but by nature shy away from the steeper slopes. Generally fair game to hunters, the more sure-footed sheep and goats are uncommon near villages. When present, sheep and goats remove the tall grass, as related above in the case of Eiaone. *Miscanthus floridulus* would appear to be rather coarse fodder, but both horses and cattle eat it readily, particularly when it is putting out tender new shoots.

At Vaipaee, the once extensive herds of cattle and horses on the high ridges west and north of the valley had been removed over a year prior to 1964. The peculiarities of plant cover there still reflected their presence, however. At the brink of every *Miscanthus*-clad precipice, where the slopes at the top would have invited the presence of the large livestock, the tall grass abruptly gave way above to transitional scrub or range cover.

Transitional Forest Cover Types

The forest of the transitional zone is richer in arborescent species than any other spontaneous vegetation at low elevation. Certain tree species aggregate in groves. Others appear throughout the transitional zone, both as forest and scattered in scrub and *Miscanthus* grassland.

Two species best characterize the forest by their abundance over all its range: *Xylosma suaveolens* subsp. *pubigerum* (*pi'api'au*), and *Sapindus saponaria* (*koku'u*).

In the shade of their closed canopy, the forest types exclude most herbaceous ground cover. As a rule, much bare soil is visible between fallen leaves and litter, and the undergrowth, if any, comprises tree shoots, scattered ferns and scant growth of *Oplismenus compositus*. *Xylosma* positively inhibits all other growth beneath its crown.

On its pluviotropical margin, transitional forest grades into *Hibiscus tiliaceus* forest or gives way to *Gleichenia* fernbrake. Where the forest extends all the way to the xerotropical margin with no interposition of other transitional cover types, it gives way rather abruptly to inland xerotropical cover.

Transitional Forest in Valley Bottoms and Ravines Above the Sea

This forest type or its remnants is frequently encountered around the shore, in uninhabited valleys behind small bays, on talus below sea cliffs, and in the plunging ravines and foreshortened hanging valleys above the cliffs themselves.

From a distance the assemblage of trees presents an airy lightness and diversity of foliage textures reminiscent of North American deciduous forests in late spring. Foliage is a light, bright green. Grey-white trunks prevail. The trees are of uneven heights, and the great banyans (*Ficus prolixa*) tower here and there above all the others. Close inspection reveals tropical growth habits: massive coalescing trunks and pendant aerial roots of the banyans, bar-like prop-roots of *Pandanus* angling stiffly outward from its trunk, and the curious ground-clasping roots of *Pisonia* that appear to flow octopus-like about and over rocks.

On the other hand, groves of *Xylosma* resemble nothing as much as a forest of birches or aspens except for their seasonal clusters of small black berries. *Xylosma* bark is light grey. Its leaves oscillate in the wind on long, pendant twigs; and yellow and fallen, they litter the otherwise barren ground beneath.

The forest in the ravines above Puamau Bay at the foot of Mt. Namana is typical. Trees include the common *Xylosma* and *Sapindus*, as well as *Thespesia populnea* (*mi'o*), *Erythrina variegata* (*netae*), *Ficus prolixa* (*aoa*), *Hibiscus tiliaceus* (*hau, fau*), *Carica papaya* (*vi papai*), *Morinda citrifolia* (*noni*), *Canthium odoratum* (*kotai*), *Pisonia grandis* (*pu'atea*), *Pandanus tectorius* (*ha'a, fa'a*), and *Premna serratifolia* (*va'o va'o*). Deep in the ravines occasional *Aleurites moluccana* (*ama*) and *hau* suggest the presence of perennial moisture there.

In similar groves elsewhere *Celtis pacifica* appears occasionally, as in long-abandoned Natue Valley, east of Puamau. In a few valley bottoms distant from habitation, *Cordia subcordata* (*tou*), a marketable cabinet timber, still occupies a sub-dominant position in the forest, as again, at Natue.

Finally, certain economic species, planted or spontaneous, appear sporadically in these same ravines and valleys, including *Capsicum frutescens* (*neva*), *Ceiba pentandra*

(*uru uru*), oranges (*anani*). Coconut palms appear where droughts are not too severe or where ground water is available and so often occupy a small area at the foot of a ravine just behind the shore.

Transitional Forests on Upland Slopes and Inland Ridgecrests

Most of the trees listed in the foregoing section appear also in the upland transitional forest. *Cordia subcordata*, however, was not encountered away from the valley bottoms, and *Celtis pacifica* and *Pisonia grandis* are uncommon far inland of coastal and xerotropical localities.

All too often the transitional zone near large settlements is sufficiently disturbed that forest stands, unbroken by new or old garden clearings, burns, and the like, are not extensive. The situation gives rise to a landscape mosaic of forest interrupted by gardens, thicket, *Miscanthus* grasslands, and denuded places. This is the situation that prevails at Puamau just south of Mt. Namana.

Closed forest nearly always includes *pi'api'au* and *koku'u* as co-dominants except as the latter is in local demand to fire bakers' ovens as at Puamau. *Mi'o*, also in demand by local wood carvers, is not prominent in the closed forest but may be common in upland parkland at forest margins.

Along ridgecrests, salients of transitional cover rise above the pluviotropical vegetation that prevails in the inland valleys. In addition to the trees listed above, several pluviotropical trees here enter the forest including prominently: *Pandanus tectorius* and *Hibiscus tiliaceus*, and also *Glochidion* sp., *Canthium barbatum*, *Coffea arabica* (except on Uahuka), and occasionally *Cocos nucifera* and *Mangifera indica*.

The profile of these ridgecrests is also marked by discrete groves of *Pandanus* and *Casuarina*, now discussed separately.

Pandanus Groves in the Transitional Zone

Pandanus tectorius abounds in the Marquesan interior throughout the transitional and pluviotropical zones. Whatever its importance in traditional economy may have been, the species is entirely feral today. I never once saw *Pandanus* used for thatch in the Marquesas. For plaitwork, the spineless, cultivated *P. tectorius* variety *laevis* is exclusively utilized. The latter bears only a Tahitian name, *paeore*. Presumably, it is not indigenous to the traditional Marquesan economy.

The wild pandan grows rarely behind the beach. Where moister zones approach the sea, however, *Pandanus* may be seen atop cliffed peninsular interfluves and in the plunging ravines that at intervals notch the barren coastal cliffs.

It is common to see groves extensive enough to form a distinct cover type and most conspicuously perhaps, in the ridgetop groves that cover rocky outcrops and old stone platforms, and up and down ravines within *Miscanthus* tall grasslands.

The appearance of *Pandanus* in *Miscanthus* tall grassland is interesting from the point of view of fire and succession. Several residents at Puamau asserted that fire kills *Pandanus*. The reliable informant, Henry Lie, added that "fire cooks the roots". One may hold reservations about the lethal effect on *Pandanus* of every light fire that might sweep by the trees, but in certain common circumstances, such destruction may be readily conceived.

In the course of a drought, decomposition of litter is arrested. The strap-like dead leaves, a meter or more in length, fall and accumulate beneath the crown and around the prop-roots in a high, loose pile. If the trees are also situated in a tall *Miscanthus* grassland, so much tinder-dry fuel would be available on all sides that fire sweeping the area would generate high heat. Survival of the pandans through such a conflagration would be remarkable, indeed.

Young trees are present in many grassland localities, attesting to lively seedling reproduction. Again, hot fires, were they to occur, would probably kill most of them.

Lacking more data, the role of fire in *Miscanthus-Pandanus* relationships remains moot, and interpretation of the status of present groves is difficult.

Surely, it would favor the maturation of *Pandanus* forests if burning stopped. On the other hand, the effect of many lighter fires, set at a time when the available fuel was scant or too damp to burn well, might serve the same effect, if the trees and seedlings were not all killed in a series of light ground fires.

The canopy of a mature grove of *Pandanus* is sometimes quite closed. The resulting shade and abundant litter then preclude much undergrowth. Here and there, however, sun-seeking *Psidium* preserves a place in the sun by assuming a very attenuated habit of growth, depending in part upon the larger *Pandanus* trees to support the spindly guava branches.

Groves and Forests of *Casuarina (Toa)*

Distinctive features of buttress ridgecrests in most valleys are groves of *Casuarina equisetifolia* (*toa*), a native tree of pinelike habit. In many other countries it is associated with maritime environments, but in the Marquesas, *C. equisetifolia* grows only incidentally near the sea and is common in the uplands in both transitional and pluviotropical zones. The ridgetop habitat is rather characteristic above the villages, but in fact, the tree thrives in a range of environments. Forests of *toa* cover steep, goat-grazed slopes in southern Eiaone, just west of Puamau. Elsewhere, *toa* forests dozens of hectares in extent, occur at 100-400m elevation on broad slopes in leeward Nukuhiva and Hivaoa and in the uplands of northern Tahuata. The species tolerates infertile soil and grows here and there in *Gleichenia* fernbrakes on all but sterile residual latosols.

In aboriginal times, the heartwood of *toa*, all but metal-hard, durably served Marquesans when fashioned into implements of war, so that widespread inland establishment of the tree may have been encouraged by Polynesian hands.

As *Casuarina* sheds its long, fine needle-like foliage, the duff accumulates rapidly to a depth of ten cm or more. Herbs grow sparsely in this loose, dry litter; a few scattered individuals of *Emilia sonchifolia* and *Polypodium scolopendria* are typical. At Puamau, two shrubs often appear in the soft shade on duff-covered ground—*Canthium barbatum* and *Canthium odoratum*. At Vaipaee one *Casuarina* grove was encircled by saplings of *Glochidion* sp. In the uplands of Tahuata, extensive groves of *Coffea arabica* grow amongst the *toa*.

Egler (1952, 252-256) has enumerated some of the ecological requirements of *C. equisetifolia*. Fire kills the tree, but the seeds germinate well in many burned-over sites. Strictly heliotropic, the seedlings require open sunny sites and bare mineral soil or rock. Once established, however, individuals may live for many decades if sheltered from fire.

Thus, the presence of *C. equisetifolia* on a site assures that the ground was barren of growth when seedlings established themselves and that the site has not since been burned over. Abundant growth of young-to-mature *Casuarina* trees aligned along the axes of ridgecrests around inhabited valleys seem to have sprouted along former open pathways where animal and human disturbance was once intense but more recently diminished, as hunting pressure upon feral herds has locally eliminated the animals, and as outboard-powered boats reduce the need for overland equestrian traffic.

Thickets of *Leucaena leucocephala*

Outstanding among the exotic plants that have assumed local dominance in fallow regrowth is *Leucaena leucocephala* (*atiko*; Fr. *acacia*), a deep-rooted tree of whipstem sapling habit that forms close stands. A deciduous, drought-resistant plant, *L. leucocephala* derives ultimately from Central American savannas. This leguminous tree, has spread slowly in the Marquesas; but where established, it has persisted tenaciously in both transitional and inland xerotropical localities. Thickets 6-8m tall and stem diameters up to 10cm are quite usual around Taiohae Bay, which is also a likely introduction site.

The areas of widespread establishment are limited to the islands of Nukuhiva and Uapou. For the record, on Hivaoa, two very local populations exist in Puamau village.

The attention of itinerant natural scientists has been drawn to the *Leucaena* thicket that extends more or less contiguously over most of the rugged terrain of southern Nukuhiva below 750m from Hakaui on the west to the heights east of Taiohae Bay, the port of entry.

Isolated thickets occur on the same island at Taipivai and on the northern shore at Hatiheu. On Uapou, additional large thickets, which I viewed from the sea but did not disembark to visit, extend over entire small valleys on the southern and western parts of the island. The largest valleys there, Hakahetau and Hakahau, have so far escaped being overrun. At Hakahau, small thickets occupy a few hollows on the slopes above the village; and at Hakahetau, I encountered a solitary individual on the dry slope above and west of the Catholic mission.

All ground cover is excluded within the thicket except in clearings or natural openings. Curiously, the shade of the foliage in full leaf is light and diffuse, suggesting that some factor besides shading accounts for the lack of undergrowth. The surface of the soil is covered by a thin blanket of duff composed of the fallen fine leaflets, twigs and petioles. No tendency toward a succession by native or introduced trees was observed (see Egler 1947, 417), even in senescent *Leucaena* stands where old trees become ungainly, lose their erect habit, and lean more or less perpendicular to the slope.

On one site at the xerotropical margin, on slopes above the eastern shore of Taiohae Bay, the *Leucaena* thickets grade into a seaward xerotropical cover, here much grazed by goats. The latter locality is notable for another peculiarity of site: the local abundance of *Acacia farnesiana*, which does not, however, yield dominance to *Leucaena* except in one or two ravines.

Inland, within the great Taiohae amphitheatre, the thickets occupy most of the lower portions of buttress ridges and other prominences about the valley that were probably once occupied by *Miscanthus floridulus* tall grass. In the ravines, *Leucaena* thickets give way to *Hibiscus tiliaceus* forest, but even here *Leucaena* invades cleared places and neglected coconut groves. In such open moist sites *Leucaena* grows well, maintaining foliage and

continuous growth for extended periods, to the chagrin of gardeners who would prefer to cope with less vigorous weeds.

In upland pluviotropical situations, *L. leucocephala* is less weedy and is encountered seldom in pluviotropical sites with residual soils. Tercinier, in personal communication, has suggested that the plant requires a calcium concentration not retained in the well-leached upland lateritic soils. The observed Nukuhivan habitats of *Leucaena* appear to bear out his suggestion, i.e., relatively xeric zones, skeletal soils on very steep slopes with much unweathered parent rock at the surface, and colluvial valley soils in the more moist localities.

Leucaena has extended its range rather slowly. The tree has been present at Taiohae for nearly a century at least (Drake 1893, 58-59) and remains local. Dry, ripe pods dehisced explosively on hot days at Taiohae, scattering the seeds several meters from the parent plant. More effective dispersal perhaps may be the scattering of seeds in the excrement of domestic and feral animals.

The plant is in disfavor in the Marquesas, and no effort to deliberately extend the range of the plant would be welcomed. Few recognize the several potentially great advantages of *Leucaena leucocephala*: as a source of protein-rich cattle forage and of very high-quality charcoal, and as a replenisher of soil nitrogen (Takahashi & Ripperton 1949). More immediate considerations in the minds of Taiohae resident are negative ones: the strenuous labor that clearing the thicket demands, and the unfortunate depilatory effect of the plant upon horses. Horses relish *Leucaena* foliage but lose all the long hair from their manes and tails after they eat it.

THE PLUVIOTROPICAL ZONE AND PLUVIOTROPICAL COVER TYPES

The pluviotropical, or moist, zone lies inland of the transitional zone and extends to the margins of the summit forest which is rich in species peculiar to the Marquesas and presumably much less disturbed in the course of human history than the sites that will be emphasized here. Included in the zone are all the interior forest types dominated by *Hibiscus tiliaceus*. Elevations begin near sea level in certain localities and extend higher than 900m.

Back Valley Forest

A number of garden trees persist for decades after a subsistence garden is left to grow back to forest. Inhabitants visit certain of these trees at intervals to collect their fruit. That is particularly true of coconuts, less so of breadfruit, but no grove of *Musa troglodytarum* (*hu'etu*), however remote from the village, may properly be called abandoned. Around such trees, a certain amount of clearing facilitates harvest activity, and an array of pluviotropical weeds grows in the resultant islands of sunlit ground within the forest.

In general, however, in those ravines farthest upvalley from the villages or difficult of access, few of the currently esteemed economic plants have persisted. It is likely that the more remote localities have remained out of cultivation 100 years or more, since the time of great depopulation (Schmitt 1965). That habitation—and with it, cultivation—once prevailed in these now lonely places is evidenced by the extensive stoneworks that everywhere occupy the gentler slopes.

Hau-Ihi (Hibiscus tiliaceus—Inocarpus fagifer) Forest of Backvalley Ravines and Box Canyons

In these very moist, fertile localities, conditions for pluviotropical plant growth probably approach a Marquesan optimum. Curiously, however, species diversity there is minimal in the mature forest. Of the available flora only two trees, *Hibiscus tiliaceus* (*hau*) and *Inocarpus fagifer* (*ihi*), dominate the mature forest, attaining heights of 10-15m. So dense is the shade beneath the foliage canopy that no herbaceous species tolerates the gloom.

A qualified exception is *Coffea arabica* (*kafe*) seedlings, which sprout by thousands, as described above. A fraction of them grow into spindly trees, 2-3m tall, to form a true understory. *Coffea* has invaded the pluviotropical forest of all the islands but Uahuka, where the plant is still common only in cultivation.

Ihi forms discrete groves, faring well in waterlogged soil, in streams, and along their banks. Sometimes it dominates the whole forest, as on the steep accumulations of talus and soil immediately below the cliffs of western Tahuata. Its dark yellow-green foliage distinguishes it at a distance from the equally somber but blue-green *hau*.

Aside from *hau* and *ihi*, few large trees prevail in the dank ravine bottom, excepting the long-lived banyan—*Ficus prolixa* (*aoa*)—and *Aleurites moluccana* (*ama*), *Terminalia* sp. (*mai'i*), and *Spondias dulcis* (*vi*, or *vi tahiti*).

Hau Forest on Backvalley Slopes

Above the deeper ravines, on the steep slopes of the backvalleys, *ihi* becomes uncommon and *hau* dominates the forest. Higher still, along and immediately below buttress ridge crests, *Pandanus tectorius* may in turn assume local dominance over *hau*.

Stature of this forest is shorter than in the ravine bottoms, around 5m for most trees, and the canopy is less dense, admitting enough light to support an herbaceous ground cover beneath a sparse shrubby understorey.

Coffea arabica flourishes in the understorey and is often dominant in it. Other shrubs and small trees in the understorey are: *Canthium barbatum*, *Glochidion* sp., *Wikstroemia coriacea*, *Morinda citrifolia*, and *Piper latifolium*. *Pipturus argenteus* appeared occasionally in such forests at Vaipaee. *Vanilla planifolia*, a succulent liana escaped from cultivation, festoons itself here and there among the branches in Puamau and many other valleys.

In the diffuse shade, *Oplismenus compositus* affords a sparse-to-dense ground cover. This grass prevails in the interior parts of Vaipaee. Several of the common ferns appear occasionally amongst the grass, notably *Nephrolepis biserrata*, *N. hirsutula*, and *Polypodium scolopendria*.

Depending on the locality, the *hau* forest grades variously into the mixed *Hibiscus-Pandanus* forest of the pluviotropical uplands, into transitional forest, or into ridgecrest cover types.

Bamboo Thickets

Discrete thickets of bamboo (*kohe*) appear erratically on slopes and broad interfluves in the pluviotropical zone, where they seem to persist remarkably well. F. Brown (1931, 91-92) names the bamboo *Schizostachyum glaucifolium* Munro, and calls the species indigenous to the archipelago.

Local needs for bamboo, for poles and light construction, are met largely from these groves.

Mango Groves

More common than bamboo thickets are imposing groves of *Mangifera indica* (*mako*) that occupy a space of a hectare or more in extent in the back valleys. Beneath the dense foliage of a mature grove, no other plant propagates but the mango itself, and its seedlings and root shoots may there form a dense thicket. Some of the groves increase in size if not actively discouraged. Mango persists exceedingly well in fallow regrowth. Swine root in the groves when fruit falls and probably help disperse the large seeds. Upon falling, fruits may roll several meters downhill on the steeper slopes, so that gravity plays a dispersal role. Old trees grow tall enough to rival coconut palms and banyans in height.

Hau He'e Forest Cover

The dominant in this cover type is the sterile form (*hau he'e, fau fe'e*) of the interesting dimorphic *Hibiscus tiliaceus* var. *sterilis*, which is quite probably an aboriginal cultigen, as it does not flower and must be propagated from cuttings. The fertile form, which the Marquesans call *hau ku'a*, resembles the prevalent local varieties of *H. tiliaceus*, and it reportedly flowers and sets seed normally.

Hau he'e, on the other hand, is different in most respects, easy to spy from a distance by its unusually slender, erect trunks, up to 20m tall. Close by, its leaves are seen to be one-third the size of ordinary *hau*, apiculate, and much more numerous on the branchlets.

I have seen both forms sprouting from the same cut stump, so that *hau he'e* appears to be a sport or chimaera, arising from the fertile form.

Hau he'e stems meet the local demand for long, slender, resilient poles in construction and as the handles of 10-to-15m long breadfruit-picking tools. In response to such need, *hau he'e* is cultivated to some extent, and small groves of it are to be seen on all the inhabited islands.

But there are very extensive stands of *hau he'e* at Vaipaee and elsewhere on Uahuka that far exceed any conceivable local need for long poles. *Hau he'e* dominates the fallow forest in the ravines in the northwest of Vaipaee. In a vegetatively propagated tree, its vigor and dominance there is worthy of note. It seems to occur in droughtier places than ordinary *hau* and upon the higher parts of slopes, but of course its occurrence may reflect old planting patterns more than ecological requirements.

Gleichenia Fernbrake

The pale, yellow-green fernbrakes of *Gleichenia linearis* are the most arresting element in the pluviotropical landscape. They stand forth as conspicuously there in the

vegetation mosaic as *Miscanthus* tall grassland does in the transitional zone. Both these cover types tend to occupy visibly prominent ridges and owe their maintenance to periodic burning.

The fern cover, like *Miscanthus*, occurs in great swaths on ascending buttress ridges around the valley margins, and the two cover types merge one into the other along an apparent moisture gradient. *Gleichenia*, unlike *Miscanthus*, appears not to thrive on the thin soil of steep, rocky slopes and seems to favor ridges with deeper soil and in fact, attains its most widespread development on the rolling-to-level deep latosols of the upland interfluves. Fernbrakes on the buttress ridges around the valleys are thus relatively minor facets of a cover type that becomes much more important at elevations between 300 and 900m.

Plate 5: Pluviotropical plant cover in Vaikivi, central Uahuka (elevation 435m); view toward southeast with island's summit (elevation 887m) in clouds at top left. The horse trail traverses *Gleichenia linearis* fernbrake. *Hibiscus tiliaceus* is dominant in the forest up to the clouds. *Pandanus tectorius* is co-dominant with it on the wooded ridges and nearer slopes here.

Observation in Hawaii, including quadrat studies, has established *G. linearis* as a fire-resistant plant and invasive in certain disturbed forest localities. Further, once established, the fernbrake appears relatively stable as a cover type, appearing to crowd out shoots of most other plants (Hosaka 1937; Kartawinata & Mueller-Dombois; MacCaughey; Vogl,44-46).

In vigorous, unbroken stands of *Gleichenia linearis*, few other plants occur in any but incidental abundance with the notable exception of the club moss, *Lycopodium cernuum*. Locally, groves of *Casuarina equisetifolia* seem to be invading the fernbrake, but the extensive development of this tendency would seem to be precluded by the sensitivity of *Casuarina* to fire.

Unlike the *Hisbiscus*-dominated pluviotropical forest, which is normally too moist to ignite, the fernbrake will burn after a few successive rainless days. Combustability is enhanced if the fernbrake has not been burned for several years, because in time the perennially ramifying dichotomous growth forms an accumulated tangle of dead stipes and fronds up to a meter or more deep, loosely matted beneath a sparse, coriaceous living canopy. Pertinently, the older the growth, the more difficult it is to traverse, and a frustrated hunter may set it afire simply to clear the way.

In Hawaii, *G. linearis* does not always succeed itself after burning. More often than not, burning this cover type in Hawaii seems to stimulate germination of grasses and woody species instead (Kartawinata & Mueller-Dombois; Vogl).

In the Marquesas, where none of the Hawaiian competitor species of *Gleichenia* are present, the regular succession of this fern by itself after burning is far more predictable. In the interior of Hivaoa, I observed *Gleichenia* sprouting from underground rhizomes in the ashes of a light burn of a low fernbrake that had been about 20cm tall. Elsewhere, the reports of informants about past burns were supported by other evidence, usually charred snags of trees in the midst of otherwise unbroken fernbrake.

Gleichenia does not bear repeated trampling. The plant is not palatable to livestock, but where horses and cattle traverse them, the fernbrakes are crisscrossed by countless lines of broken and trampled foliage. Under repeated trampling, the plant is unable to maintain its brittle stipes although the tangled fronds often overhang trails where they grow on slopes above the height of the animals' heads.

Within such stock-opened fernbrakes, several other species enter the cover along with *Gleichenia* and *Lycopodium*. In the uplands behind Puamau where horses are freed to rest and fatten, trampling is extensive and the grass-like sedge, *Cyperus brevifolius*, and a coarse herb, *Elephantopus mollis* (*fotapa*) are very common among the disturbed ferns. *Paspalum paniculatum* (*pufaro*), also grows among the ferns and locally forms relatively pure stands.

In the interior of Nukuhiva, in the Tovii basin, the *Gleichenia-Paspalum* association is very extensive. There, *Gleichenia* also associates itself with *Metrosideros* sp. in a kind of open fern savanna that is not elsewhere usual in the Marquesas but will be very familiar to students of vegetation in Hawaii, the Society and Cook Islands.

In both Nukuhiva and Hivaoa, *Paspalum conjugatum* is another grass often seen in the moist, grazed uplands but almost always in swales and in the semi-shade of open woods. Rather amazingly, *P. conjugatum* was entirely absent from Uahuka in 1964, as far as I could tell in three months' field work.

Where grazing animals are not present in the fernbrake, as at Vaikivi, above the fall line in the upper reaches of Vaipaee Valley on Uahuka, the mat of fern cover is unbroken where it occurs, and the grasses and other herbs are to be found only in the path that traverses the region. In Vaikivi I could observe no tendency of the fern to invade and displace the pluviotropical forest. *Gleichenia linearis* does not grow in the shade of an unbroken *Hibiscus tiliaceus* canopy. In Vaikivi, the fernbrake had grown several years without burning. The mat of fern terminated abruptly at the edge of the foliage canopy of the forest, which was about three meters tall on the slopes. Except for a border of *Polypodium scolopendria* and *Ageratum conyzoides* in the narrow band of brighter light just beneath the thin edge of the forest canopy, a sparse cover of the shade-tolerant grass, *Oplismenus compositus* prevailed beneath the trees.

In sum, in the pluviotropical zone on poorer residual latosols, *Gleichenia* fernbrake is the most likely cover type in the presence of burning alone, giving way under the shade of *Hibiscus tiliaceus* and other trees, or, in the presence of both fire and animal pressures, to mixed *Gleichenia* and *Paspalum* grasses and other herbs.

SOURCES CITED

Adamson, A. M.
1936 Marquesan Insects: Environment. *Bernice P. Bishop Museum Bulletin* 139:1-73, 8 plates.

Brown, Elizabeth D. W., and Forest B. H. Brown
1931 Flora of Southeastern Polynesia II. Pteridophytes. *Bernice P. Bishop Museum Bulletin* 89:1-123.

Brown, Forest B. H.
1931 Flora of Southeastern Polynesia I. Monocotyledons. *Bernice P. Bishop Museum Bulletin* 84:1-194.

1935 Flora of Southeastern Polyesia III. Dicotyledons. *Bernice P. Bishop Museum Bulletin* 130:1-386.

Crook, William Pascoe
1797-1799 Anonymous [Ed.]. *The Mitchell Library Crook MS*; in Sheahan[1952], cxiii-clxxxiii.

[Anonymous Ed.] *An Essay Toward a Dictionary and Grammar of the Lesser-Australian Language, According to the Dialect Used at the Marquesas. Compiled from the Collections and Information of William Crook, Who was Sent to Those Islands by The Missionary Society, and Resided at Them from 6 June 1797 to 8 Jany. 1799*; in Sheahan [1952],liii-cxii.

Decker, Bryce Gilmore
1970 *Plants, Man and Landscape in Marquesan Valleys, French Polynesia* University of California, Berkeley. Doctoral dissertation (Geography). 324 typescript pages. Also Xerox University Microfilms 71-9790, 1971.

Drake del Castillo, E.
1893 *Flore de la Polynésie française*. Paris: G. Masson, 352 pages.

Egler, Frank E.
1939 Vegetation Zones of Oahu, Hawaii. *Empire Forestry Journal* 18:44-47.

1942 Indigene Versus Alien in the Development of Arid Hawaiian Vegetation. *Ecology* 23:14-23.

1947 Arid Southeast Oahu Vegetation, Hawaii. *Ecological Monographs* 17:383-435

1952 Southeast Saline Everglades Vegetation, Florida, and its Management. *Vegetatio* 3:213-265.

Forster, Georg
1777 *A Voyage Round the World, in His Britannic Majesty's Sloop*, Resolution, Vol. II, B. London: B. White, 607 pages.

Fosberg, F. R.
1972 *Field Guide to Excursion III, Tenth Pacific Science Congress, Revised Edition.* Honolulu: Department of Botany, University of Hawaii. 249 pages.

Guppy, H. B.
1906 *Observations of a Naturalist in the Pacific between 1896 and 1899 II: Plant-Dispersal.* London: Macmillan. 627 pages.

1917 *Plants, Seeds, and Currents in the West Indies and Azores.* London: Williams and Norgate. 531 pages.

Hosaka, Edward Y.
1937 Ecolgical and Florisitic Studies in Kipapa Gulch, Oahu. *Occasional Papers of Bernice P. Bishop Museum* 13:175-232.

Index Herbariorum, Part I: *The Herbaria of the World.*
1981 Seventh edition. The Hague/Boston: W. Junk B.V. 452 pages.

Kartawinata, K., and D. Mueller-Dombois
1972 Phytosociology and Ecology of the Natural Dry-Grass Communities on Oahu, Hawaii. *Reinwardtia* (Bogor) 8:369-494.

McCaughey, V.
1920 Hawaii's Tapestry Forests. *Botanical Gazette* 70: 137-147.

Papy, H. René
1948 Aperçu sommaire des étages de végétation à Tahiti. *Travaux du Laboratoire Forestier de Toulouse* (Tome 5, section 2, volume 1), art. 1, 1-6.

1954 Tahiti et les îles voisines: la végétation des Iles de la Société et de Makatea (Océanie française) [1]. *Travaux du Laboratoire Forestier de Toulouse* (Tome 5, section 2, volume 1), art. 3, 1-162.

[1955] *Tahiti et les îles voisines*: ... 2. ... art. 3, 163-386.

Ripperton, J. C., and E. Y. Hosaka
1942 Vegetation Zones of Hawaii. *Hawaii Agricultural Experiment Station Bulletin* 89:1-60.

Schmitt, Robert C.
1965 Garbled population estimates of Central Polynesia. *Journal of the Polynesian Society* 74:57-62.

Schwartz, Charles W., and E. R. Schwartz
1949 *A Reconnaissance of the Game Birds in Hawaii.* Hilo: Territory of Hawaii, Board of Commissioners of Agriculture and Forestry, Division of Fish and Game. 168 pages.

Sheahan, George M., Editor
[1952] *Marquesan Source Materials*. Quincy, Massachusetts; [spirit duplicated by author], i-ccvii.

Takahashi, M., and J. C. Ripperton
1949 Koa Haole (*Leucaena glauca*): Its Establishment, Culture and Utilization as a Forage Crop. *University of Hawaii Agricultural Experiment Station Bulletin* 100:1-56.

Vogl, Richard J.
1969 The Role of Fire in the Evolution of the Hawaiian Flora and Vegetation. *Proceedings of the Annual Tall Timbers Fire Ecology Conference*, April 10-11: 5-60.

ATOLL RESEARCH BULLETIN

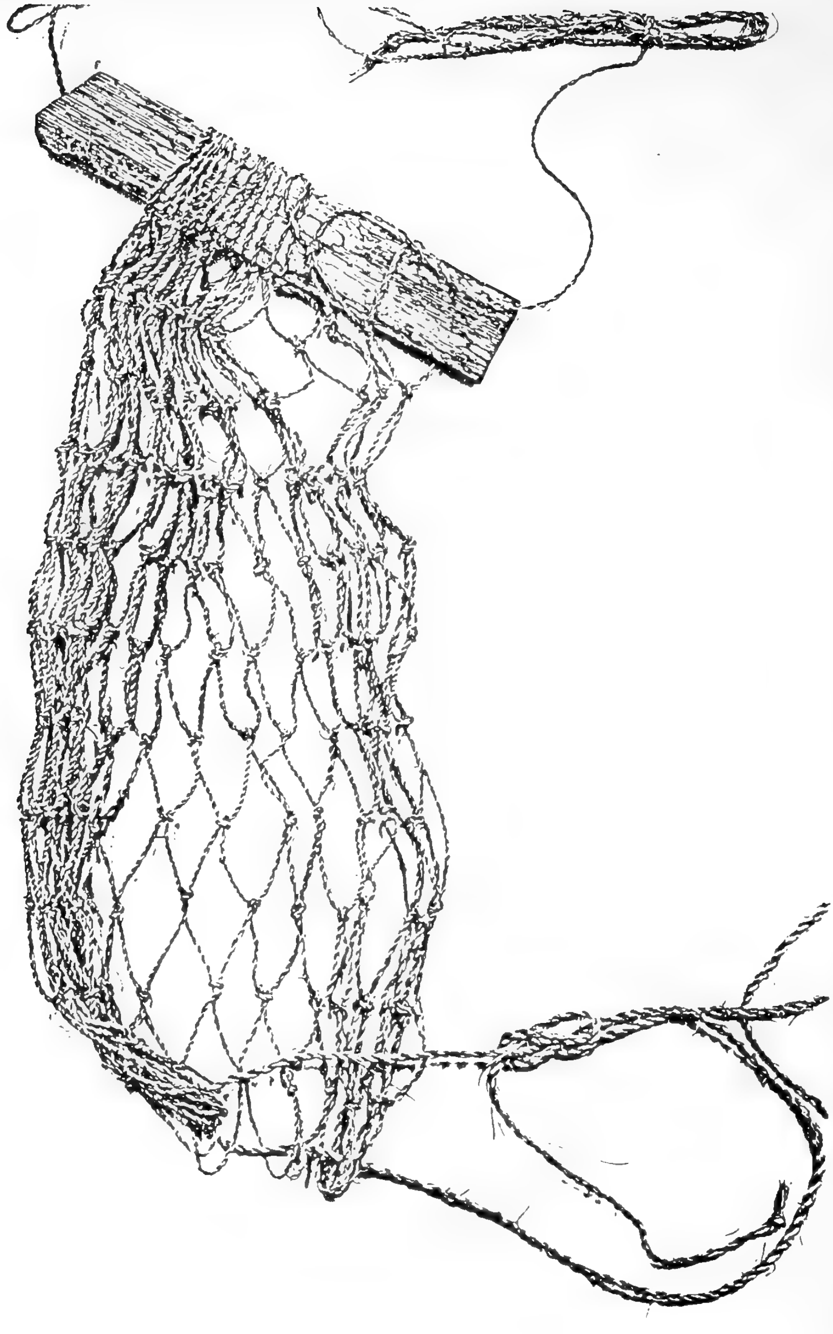
NO. 364

SEAGRASS NETS

BY

M.C. FALANRUW

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
MAY 1992



Frontispiece. A seagrass net.

SEAGRASS NETS

BY

MARGIE C. FALANRUW[1]

Illustrations by Martin Faimau[1]

Abstract

The persistent bundles of vascular fibers which characterize the seagrass *Enhalus acoroides* (L.f.) Royle, are utilized in the construction of nets which last for generations. The technology and its cultural context, illustrates a number of things about man in the island ecosystem. Since there appear to be few practitioners of the art left, the process is here described in detail. This description is extracted from an ongoing project which will relate the marine environment, species, traditional technology, and culture of the Yap islands.

Introduction

Enhalus acoroides (L.f.) Royle, is one of seven sea grasses reported for Yap (Tsuda et al. 1977), in the Western Caroline Islands. A distinguishing character of this seagrass are the tough vascular bundles which stiffen leaf margins and remain after leaves are broken or gone. These persistent strong fibers were utilized on Yap island in the construction of nets which last for generations. Such nets were in use on Yap until World War II. Today there remain only a few elders who can make these fine nets. We are grateful to Lubuw ni Ga' who introduced us to seagrass nets and to Chonmogon and Gabay (now deceased) for demonstrating the technology to us.

The nets were made in only a few villages located near bays where appropriate seagrass occurred. In the bay of Rumu' village, special marine meadows were protected so that *Enhalus acoroides* would grow long and unbroken. The fibers were then collected at low tide. Today's elders remember that when they were boys, the area would be filled with older men collecting seagrass fibers at appropriate tides. It is said that suitable seagrass grew in only a few places on Yap. Today *E. acoroides* is common in many areas of the Yap lagoon however the special beds in Rumu' are being buried in silt as a result of soil erosion from road construction.

Enhalus acoroides (figure 1) naturally curves up from a horizontal rhizome. It is said that in the past, plants in the special beds lacked the basal beard of fibers because of their frequent collection. When collected (figure 2), leaves were harvested from but one side of the plant. One informant said that this helps to conserve the resource, while another suggested that the fibers are stronger on the convex side of the plant. Prior to harvesting

[1] Yap Institute of Natural Science, Box 215, Yap FM 96943

Figure 1. *Enhalus acoroides* (L.f.) Royle (from Den Hartog 1970, p. 218).

the leaf, the collector reaches down to feel which way the rhizome is curving. He then pulls the leaves up, stripping off debris and epiphytes as he does. It is believed that this helps the sea grass to grow better. A thumb is inserted in the axil of the chosen leaf, generally the second from the outside of the plant. The fibers of the outermost leaf, likened to the fibers of a mature coconut husk, are generally broken and too stiff to be used. With the thumb held next to the base of the plant, the collector pushes down and separates the

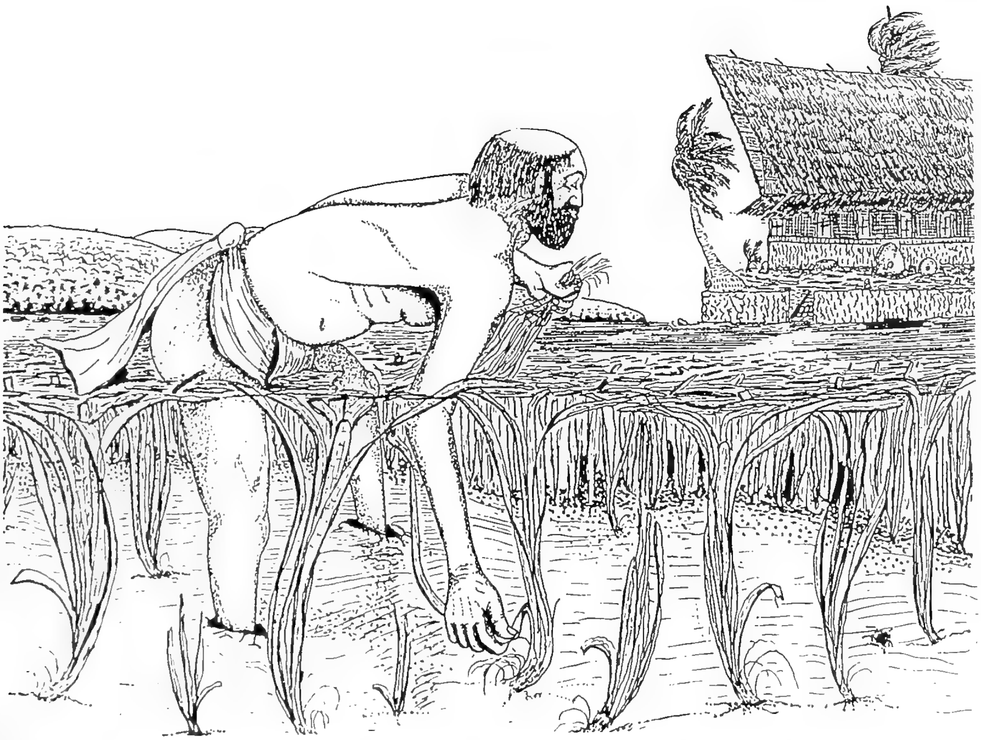


Figure 2. Collection of seagrass fibers.

leaf with minimal damage to the rest of the plant. The harvested leaf has light colored fibers extending from either side of the base. These are likened to the more supple fibers of a green coconut husk. The basal portion of the leaf is grasped in one hand and the central portion of the leaf blade is stripped away from the distal end of the blade with the thumb of the other hand. The result is a short section of the leaf blade with long strips of the leaf margin extending on either side (figure 3). The longest fibers which we observed collected on August 26, 1988 were 95 cm in length.

After a handful of such strips has been collected, they are scrubbed together section by section starting at the top and continuing all the way to the tips. They are then tied into a bundle by bending the fibers near the top and winding the distal portion around the bend from the top down. These bundles of fibers are left on top of clusters of seagrass exposed during low tide, and another bunch is collected. On his way back to shore, the collector gathers all the bundles. The bundles of fibers are brought to the stone platform of the men's house. Here they are hung on bamboo poles to dry. About a generation ago, some 9 meters of bamboo poles were required to hold all the fibers that were collected during one low tide.

Preparation of fibers

When the strips reach the right stage of dryness, the bundles of vascular tissue making up the fiber are extracted from the surrounding tube-like tissue. Extraction of the entire length of the thin pale fibers, which are only about 0.3mm in diameter, is a delicate operation requiring practice. The double strands are held firmly in one hand and then the connecting leaf blade is grasped firmly between thumb and pointer finger, and stripped off. This exposes the light colored fibers. These fibers are then held firmly and the leaf tissue surrounding the fibers like a sheath, is stripped off. This involves an initial jerk followed by a long smooth pull to slide the ensheathing tissue off. The operation is similar to pulling the drawstring out of a narrow hem, but requires a delicate touch similar to that of pulling one thread from a piece of cloth without breaking the thread. The thumbnail is used in making the initial separation but not after this, lest the fiber be broken. Should the sheath tissue get too dry, it can be wet again, and dried to the appropriate condition to be stripped off. In the old days young boys would take the left over tissue stripped from the fibers, and chew it for its salty flavor (similar to the taste of kelp of Japanese cuisine). Once extracted, the pale buff fibers are stable, and are stored until enough have been collected to prepare twine.

Preparation of Seagrass Twine

Twine is prepared by twisting seagrass fibers together. The bundle of fibers is held under one arm, and about 4-5 fibers are pulled out, the number depending on the desired thickness of the twine. Initially these fibers are twisted together with the fingers. Once firmly twisted, they are rolled on the thigh. A second strand is prepared the same way. Then the two strands are placed side by side and rolled together, first foreword, then briefly back to make the twine tight. Occasionally, when the strands are not tight, or when additional fibers are added, the 2 bunches of fibers may be separately rolled before being rolled together.

After each roll, the free strands get tangled and must be separated. This is generally done by pulling them across the knee. When new strands are added, they are placed, basal (thicker end) up, against the twisted strands and then pulled down until they are even with the end of the twisted strands already in place. Rolling the twine pulls hair from the thigh and the thighs of men who made a lot of twine got blackened and tough. Nowadays a rubber "chap" made from an inner tube is sometimes used to protect the thighs in the similar process of making coconut twine.

After a length of twine was made, strands sticking out may be trimmed off. This is not necessary, if the net is to have a large mesh, but is helpful when making a finer twine for smaller mesh nets. When the process of making twine was demonstrated to us, one person made 4 "drri"[1] (measured to total 6 meters), of twine in about 2 hours. While twine is being made, the seagrass fibers are stored in a rolled section of the basal sheath of a betelnut leaf, "wathir", with notches cut on one end. The twisted twine is then wrapped around these notches. Remaining seagrass fibers are also stored in the rolled "wathir". This "kit", is carried in the basket to be worked on when possible, such as while sitting in long meetings.

Figure 3. Collected *Enhalus* leaf showing fibers.

Preparation of the "teliyo"

The original net making "needle" was made from a stiff loop of coconut sennit with loops of the finer seagrass twine attached via an ingenious manipulation of the sennit loop and seagrass twine involving fingers of both hands and a toe (figure 4). A length of sennit is knotted into a loop. The longer the twine to be used, the longer the loop. The end of the loop opposite the knot is held in the left hand. One end of the seagrass twine is held with the toes, and a desired length measured out. The twine is bent over at this point and inserted through the sennit loop. The pointer finger is then inserted through the seagrass twine loop and the closest side of the sennit loop is pulled with the third finger (figure 4). The seagrass twine slides off the thumb, and the sennit loop is pulled up and the seagrass loop pulled down toward the knot in the sennit loop.

Another length of seagrass twine is then looped over the toe, looping it to the left (or at least always in the same direction), and then bringing it up, and making a bend. Before the bend is inserted into the sennit loop, the sennit loop is twisted so that the bend is inserted through the opposite side. The procedure described above is then repeated. This results in loops of seagrass twine hanging from alternating sides of the sennit loop. The sennit loop is used like a net needle (figure 5). When additional twine is needed, the uppermost loop of seagrass twine is easily slipped over the end of the sennit loop to release a measured length of twine.

Making nets with seagrass twine

In addition to the teliyo, a second tool called the "yeer" is employed in net making. The yeer is a flat piece of bamboo cut to the desired mesh size and used to space the net knots.

To begin the net, a length of twine is measured out, bent and wrapped around the yeer twice. It is tied with a square knot. The two ends are then wrapped around the yeer in opposite directions and tied again on the top edge of the yeer. This is repeated until the desired number of mesh have been tied to make the desired height of the net. If necessary, the mesh eyes are slid to the left off the yeer to make more room. When enough mesh have been made, the short end of the twine is cut. The other long end of twine will be used to make the rest of the net.

The second row of knots are tied differently. The twine is passed under the yeer and the teliyo inserted through the first eye of the first row and pulled down. The knot is then tied as in figure 5. Care must be taken when the knot is pulled tight to assure that the hitch catches the 2 side strands of the eye above and is tightened so that it holds them. In this way the strands will be fixed in place. The knot strand is held in place over the 2 upper strands with the thumb and/or thumb nail as it is pulled tight. The knot is then pressed to fix it. If this is not done properly and the twine is merely pulled, it will make the hitch onto

---

[1] There is no official orthography for the Yapese language, so the spelling of Yapese words is subject to variation.

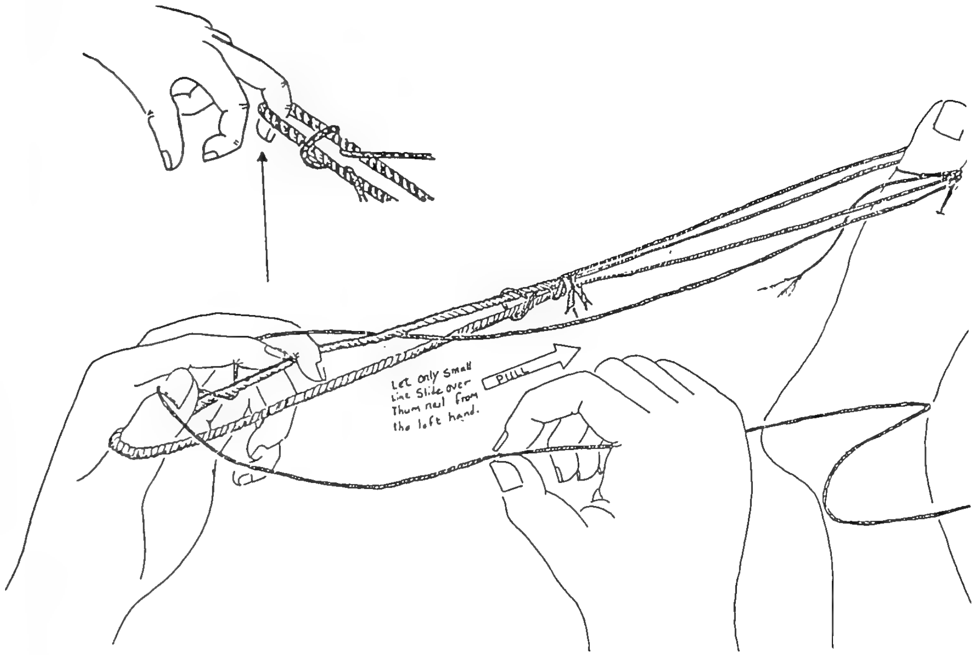


Figure 4. Preparing teliyo.

itself under the 2 strands of the upper eye and allow the upper eye to shift laterally as it pulls through the hitch. This causes friction on the single strand of twine at the lower apex of the upper eye and weakens the net. By holding the knot so that it is formed higher, over the two sides of the upper eye, the net is much stronger, and will hold its shape. Successive rows of knots are made on opposite sides of the net as the net is turned over each time the end of the row is reached.

This kind of knot is used with twine made from fibers of seagrass, coconut, hibiscus (*Hibiscus tiliaceus* L.) and pineapple. It is not used with monofilament line or when making casting nets.

The fine mesh nets were used in a variety of ways. These included hand nets (figure 6) called "k'ef", larger nets set to catch seasonal migrations of small fish, and in a special fishing method in which a large net is pulled between two sailing canoes. The last large seagrass net was purchased by a Japanese visitor to Yap, so measurements are not available. The average size of a small k'ef net is about 55 cm in height; and about 148 cm in length. Such a net would be tied to a k'ef frame about 20 cm in height. The width of the net allows an ample pocket that can be flipped over the frame, to trap fish. The net is tied to the k'ef frame with the knots and eyes forming vertical triangles. This is said to make the net less threatening to fish as the height of each mesh eye is greater than the width

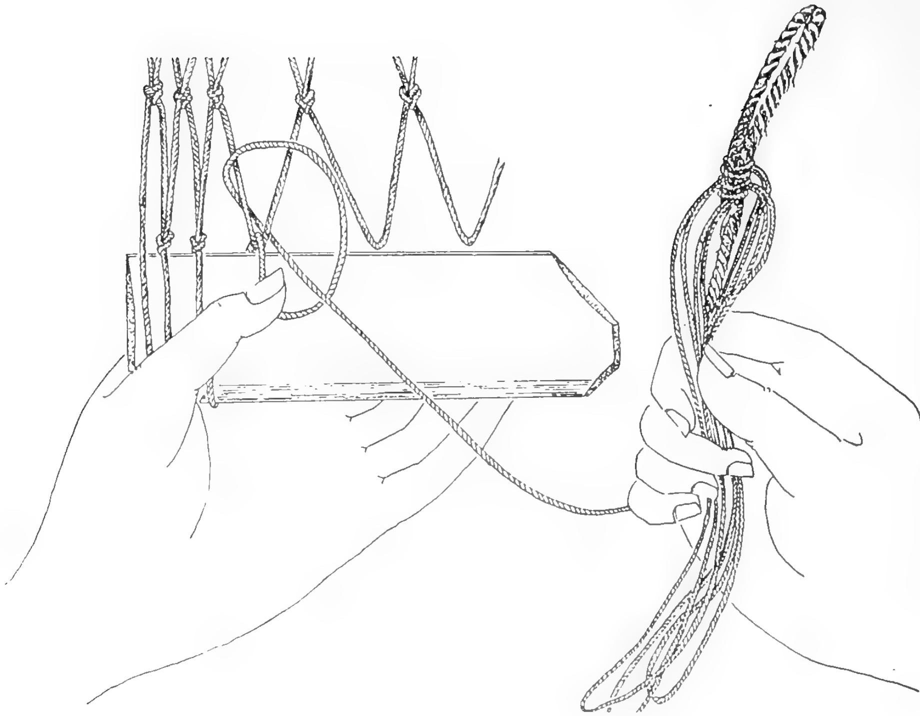


Figure 5. Use of the teliyo in making the net.

similar to the laterally compressed fish which may feel that it can swim through the mesh. The k'ef hand nets were used by individuals or groups in a variety of fishing methods (Falanruw in prep.).

Making K'ef

Figure 6 shows 3 styles of k'ef nets illustrated in Mueller (1917). It was estimated that it would take one to two months to make a pair of k'ef. The most time consuming process is the making of the net as described above. The materials used to construct this frame are collected and prepared in an appropriate sequence. Some time is required to find materials with the right bend, thickness etc. The first thing to be collected are the sticks to be used for the "ya'al", and the "gurfil". In Rumu', these are made from a certain small hardwood tree called "ya'al" (voucher specimen MVCF 5701). This tree occurs in native forest and is not very common. It has straight branches with widely spaced leaf nodes, making it especially appropriate for the ya'al of the k'ef. Other villages which do not have native forest and ya'al trees, use *Ixora casei*, ("gachiyo") for the ya'al.

A

B

C

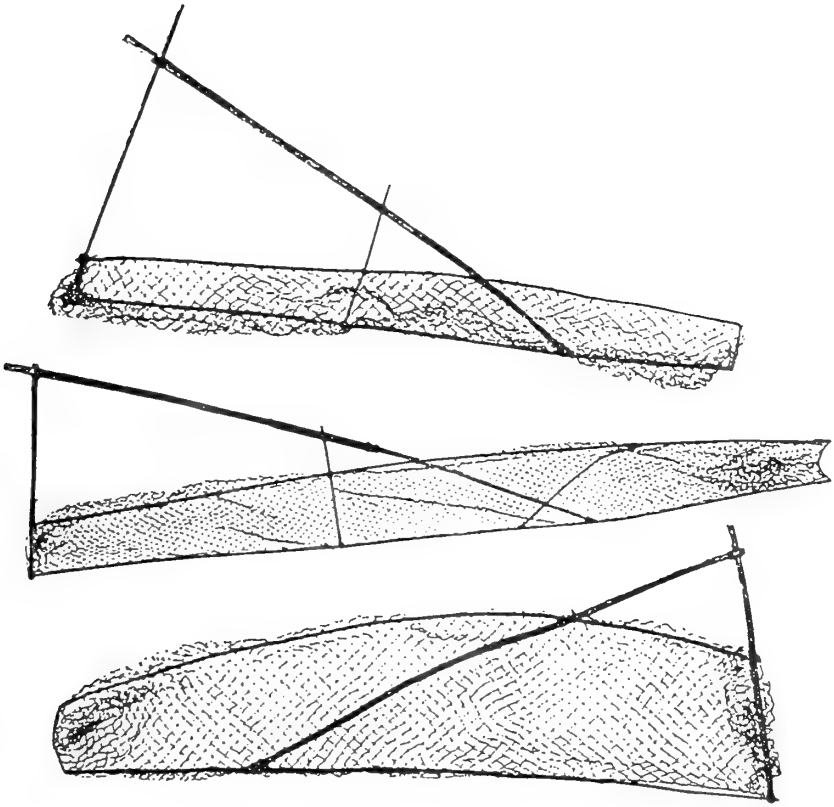


Figure 6. Some kinds of k'ef (figure and descriptions from Mueller 1917): A. Small k'ef, from Onean, 1.78 m long; B. large k'ef, Masolol from Nari, 2.95 m long; C. Wide k'ef, Uruts from Onean, 1.88 m long.

Appropriate sticks are cut from the ya'al tree and placed in salt water and weighted down so they will not be exposed at low tide. The area may have either a muddy or gravely bottom but should not have too much fresh water mixed in as this would cause the sticks to rot. The stick can stay there for years if necessary. When the sticks are retrieved for use, the bark comes off naturally. The ya'al is treated this way to make it strong so it will last a long time.

The next things to be collected are the seagrass fibers—as has been described. Other materials include pieces of large and small bamboo. Two appropriate size and shaped pieces of the large bamboo, "mor" (*Bambusa vulgaris*) are sought for making the "buk-e-richib", and "duga'". These may either be taken from the small branches at the end of a large bamboo, or from a stunted bamboo that grows in the savanna. A section of a smaller species of bamboo, "p'uw" (*Bambusa* sp.) is used for the "terwey". The piece

chosen should be the same size as the ya'al and it should be mature so it will be strong. Both types of bamboo are treated by being submerged in salt water to protect them from the insects that bore holes in bamboo. The pieces are left in salt water from about a week to a month (while waiting for the net to be completed). If left too long they will spoil.

The stem of the viny fern known as "piy", (*Lygodium circinatum*, reference specimen MVCF 360), growing in the savanna, is collected about the same time as the bamboo. It is used to connect the end of the "terwey" and the ya'al because it is flexible, yet stiff enough to maintain the spread. The piy doesn't have to be put in the salt water, just dried. Fibers extracted from the roots of coconut trees can also be used for this end piece. After the seagrass net is completed, the frame is constructed. Small gauge coconut sennit is used in tying the joints.

Care of seagrass nets

If properly cared for, seagrass nets could be used throughout a person's life and then passed on to the next generation. One of our informants had utilized his grandfather's net until it was destroyed during the Japanese occupation of Yap. After each use they were hung up to dry and protected from rain. If not used for a time, they were periodically dipped in sea water and allowed to dry again. When dry, the nets were wrapped in rolled sheaths of the basal portion of betelnut leaves (wathir) to protect them from being chewed by rats and geckoes.

Discussion

The development of a life-sustaining technology and culture based on the limited natural materials available on a small island is the creation of something that wasn't there before—no small achievement. The production of seagrass nets illustrates a number of things about man in the island ecosystem.

The *Enhalus* resource appears to have been managed. Children were not allowed to pull the seagrass up or to play in the area. The stripping of the leaves during harvest removed debris and epiphytes, probably resulting in an increase in light reaching the leaf blade. The practice of removing but one leaf per plant also contributed to the conservation of the resource. In *Enhalus acoroides*, roots are formed from axillary buds on the ventral side of the rhizome. The harvest of only one mature leaf from the dorsal side of the rhizome does not interfere with the formation of additional roots. This practice would serve to conserve the resource whether or not it was a conscious conservation strategy.

Nets were made with a conservation of energy and efficiency of movement characteristic of Yapese technology. The source of materials was near the village mens' house where the fibers were prepared. The collection of fibers was tuned to the tides. Collected fibers were bundled and laid on seagrass leaves exposed at low tide to be gathered on the return to shore with the rising tide. The processing and use of the fibers is organized, orderly and accomplished with the fewest movements needed.

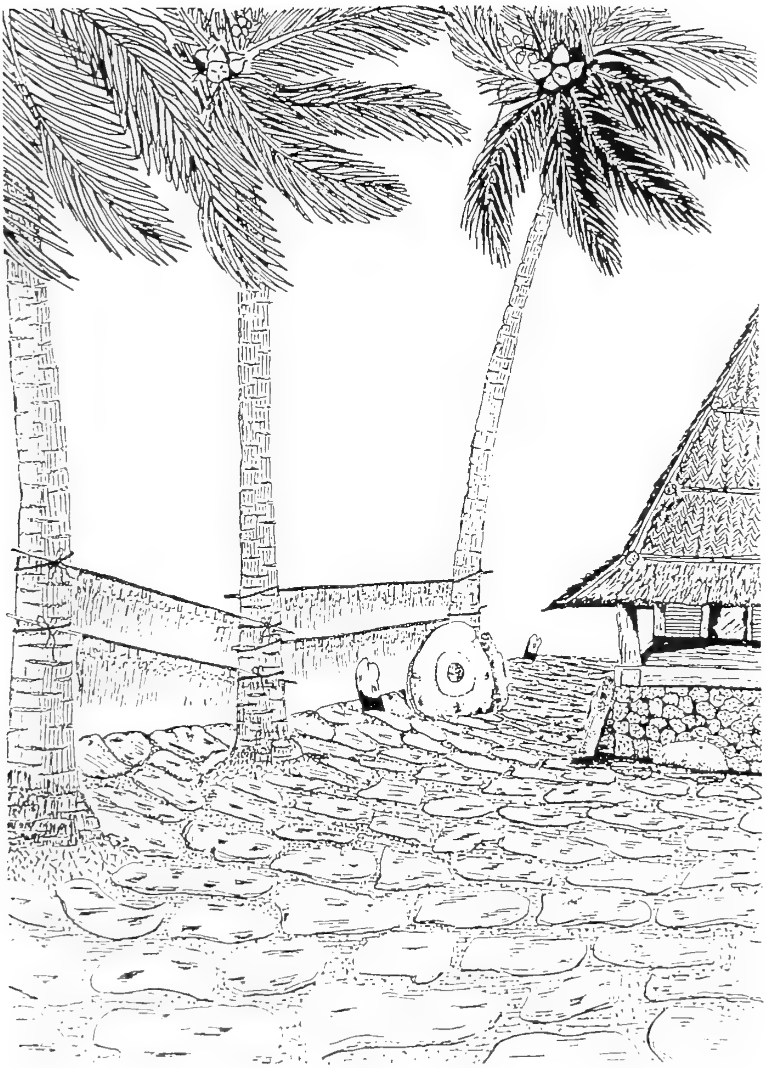


Figure 7. Large collection of leaves drying on bamboo poles near village men's house.

The strength of the thin individual fibers is limited and skill and time was required to make them into fine, durable nets. The development and practice of such a skill requires a freedom from other activities—provided by a tradition of specialization. Though seagrass nets were desired by many, making them was the specialty of a limited group, and provided a valuable medium of cultural exchange and prestige for this group. The making and use of seagrass nets also provided for a mutual exchange of talents between generations. Older men, having lost strength and gained patience, made the nets. In gathering the fibers, they shared companionship and mutual endeavor with other elders. The art of making seagrass nets is satisfying. The product is lasting and valued. Even the discarded semi-dried leaf sheaths provided a special taste treat for the children prohibited from frolicking amid the special seagrass—a taste remembered from his youth by our teacher, and now, even by us, his students. The nets were used by fishermen, who would bring their catches to the mens' house to share with the older men, who would in turn, mend any torn nets and relate their own fishing experience—thus helping to develop the next generation of fishermen, and, eventually, net makers.

References

Den Hartog, C. 1970. The Sea-Grasses of the World. Verhandelingen der Koninklijke Nederlandse Adademie Van Wetenschappen, AFD. Natuurkunde, Tweede Reeks, Deel 59, No. 1. North Holland Publishing Company, Amsterdam.

Falanruw, M.V.C. in prep. Traditional Use of Marine Resources on Yap.

Mueller, W. 1917. Yap. *In* Thilenius, G.(ed.) Ergebnisse der Sudsee Expedition. II. Ethnographie: Band 2, L. Friederichsen and Co., Hamburg, 811 p.

Tsuda, R.T., F.R. Fosberg and M.-H. Sachet. 1977. Distribution of seagrasses in Micronesia. Micronesica 13(2):191-193.

☆U.S. GOVERNMENT PRINTING OFFICE: 1992-326-918

ATOLL RESEARCH BULLETIN

NOS. 355-364